

**Final Report**

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**Dates and Location: March 1-6, 2009**

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As per the language of the grand award letter, the final report consists of a summary of scientific papers presented as well as a list of participants.

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<b>14. ABSTRACT</b> This was scientifically a very successful conference attended by about 90 people (about 15 graduate students) almost equally divided between attendees from USA (21), Asia (31), and Europe (28). In all, about 12 countries were represented by about 90% academics, with the rest from industry. The 4.5-day conference had 42-½ hour talks (most speakers used most of their 30 minutes, cutting discussion) and two poster sessions with a total of about 49 posters. Microplasmas is a growing field because of the medical applications.						
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*Program*

# **Fundamentals and Applications of Microplasmas**

**March 1- 6, 2009**

**Catamaran Resort Hotel, San Diego, California**

Tel: 1-858-488-1081

## Conference Co-chairs:

**J. Gary Eden**

University of Illinois, USA

**Sung-Jin Park**

University of Illinois, USA

**Kunihide Tachibana**

Kyoto University, Japan

**Jörg Winter**

Ruhr Universität Bochum, Germany



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## **SUNDAY, MARCH 1, 2009**

16:00 - 18:00	Registration (Kon Tiki Foyer)
18:00 – 19:00	Welcome Reception (Aviary Foyer)
19:00 – 21:00	Dinner (Aviary Ballroom)

### ***NOTES***

- **Conference participants taking part in all conference meals will have a special sticker placed on their badges. Participants who have opted out of meals will only have access to coffee breaks and social hours.**
- Technical sessions will be held in the Kon Tiki Ballroom.
- Posters may be hung in the Rousseau Suite.
- Breakfasts locations will change during the conference – please refer to the daily reader board in the main lobby for the location.
- Lunches – at Beach North (outdoor area). Please bring sunglasses and a light jacket.
- Dinners – at Beach North (outdoor area). Please bring a jacket.
- Audiotaping, videotaping and photography of presentations are strictly prohibited.
- Speakers – Please leave at least 5 minutes for questions and discussion.
- Please do not smoke at any conference functions.
- Turn your cellular telephones to vibrate or off during technical sessions.
- Be sure to make any corrections to your name/contact information on the Master Participant List or confirm that the listing is correct. A corrected copy will be sent to all participants after the conference.

**MONDAY, MARCH 2, 2009**

07:30 – 08:30	Breakfast
08:30 – 08:40	Welcome and Introduction J.G. Eden, Conference Co-Chair J. Routbort, ECI Technical Liaison
08:40 – 09:20	Plenary Speaker Ulrich Kogelschatz <b><i>“Microplasmas: Fundamental Aspects and Future Prospects”</i></b>
09:25 – 12:25	<b><i>SESSION I: THEORY AND DIAGNOSTICS OF MICROPLASMAS</i></b> <b><u>Session Chair:</u></b> K. Tachibana
09:25 – 09:55	Tsuyohito Ito Osaka University, Japan <b><i>“Electric Field Measurement in High Pressure Hydrogen Microdischarges”</i></b>
09:55 – 10:25	Volker Schulz-von der Gathen Ruhr-Universität Bochum, Germany <b><i>“Spectroscopy Based Investigation of Heating Mechanisms in Microscale Atmospheric Pressure Plasma Discharges”</i></b>
10:25 – 10:55	Coffee Break
10:55 – 11:25	Jae Koo Lee Pohang University of Science and Technology, Korea <b><i>“Atmospheric Pressure Microplasmas: Modeling and Experiments”</i></b>
11:25 – 11:55	Zoran Lj. Petrovic Institute of Physics, Serbia <b><i>“Volt-Ampere Characteristics And Diagnostics Of Micro Discharges”</i></b>
11:55 - 12:25	Yi-Kang Pu Tsinghua University, China <b><i>“Comparison Between Atmospheric Pressure Microdischarges and Low Pressure Discharges from an OES Perspective”</i></b>
12:25 – 13:30	Lunch
13:30 – 16:30	<i>Ad hoc</i> sessions and/or free time
16:30 – 17:00	Coffee Break
17:00 – 19:30	<b><i>SESSION II: NOVEL PHENOMENA AND APPLICATIONS</i></b> <b><u>Session Chair:</u></b> S.-O. Kim
17:00 – 17:30	Kay Niemax ISAS – Institute for Analytical Sciences, Dortmund, Germany <b><i>“Laser-Induced Microplasmas”</i></b>
17:30 – 18:00	Yuri Noma University of Tokyo, Japan <b><i>“Gas Temperature Dependent Generation and Diagnosis of Cryoplasma Using Dielectric Barrier Discharge (DBD) Microplasma”</i></b>

**MONDAY, MARCH 2, 2009 (continued)**

- |               |   |
|---------------|---|
| 18:00 – 18:30 | Axel Mellinger<br>Central Michigan University, USA<br><b><i>“Microplasma Discharges in Polymer Foams: A New Road to Flexible Piezoelectric Polymer Films”</i></b> |
| 18:30 – 19:00 | Leanne Pitchford<br>Université Paul Sabatier, France<br><b><i>“Microdischarges And The Generation Of Stable, Larger-Volume, High-Pressure DC Plasmas”</i></b>     |
| 19:00 – 19:30 | Kyung Cheol Choi<br>KAIST, Korea<br><b><i>“Applications of Microplasmas for Flexible Display Devices”</i></b>   |
| 19:30 – 21:30 | Dinner  |



## **TUESDAY, MARCH 3, 2008**

07:30 – 08:30	Breakfast
08:30 – 08:35	Announcements / Session Overview
08:35 – 12:35	<b>SESSION III: MICROPLASMA JETS AND TORCHES</b> <b><u>Session Chair:</u></b> J. Winter
08:35 – 09:05	Wei-Dong Zhu Saint Peter's College, USA <b><i>"Atmospheric Pressure Plasma Micro Jet"</i></b>
09:05 – 09:35	Han S. Uhm Ajou University, Korea <b><i>"Various Microplasma Jets and Their Application to Sterilization"</i></b>
09:35 – 10:05	Katsuhisa Kitano Osaka University, Japan <b><i>"Low Frequency Microplasma Jet and its Application to Plasma Induced Chemical Processes in Liquids"</i></b>
10:05 – 10:35	Coffee Break
10:35 – 11:05	Jan Benedikt Ruhr – Universität Bochum, Germany <b><i>"Analysis of Microplasma Jets by Means of Molecular Beam Mass Spectrometry"</i></b>
11:05 – 11:35	Timothy Grotjohn Michigan State University, USA <b><i>"Design of a Miniature Microwave Plasma Torch and its Operation in Plasma-Assisted Combustion and Microwave – Powered, Discharge – Only Modes"</i></b>
11:35 – 12:05	Juergen Kolb Old Dominion University, USA <b><i>"Microplasma Jet for Medical Applications"</i></b>
12:05 – 12:35	Albrecht Brockhaus Bergische Universität Wuppertal, Germany <b><i>"Plasma Bullets in Cylindrical DBDs and Piezo-Electric Surface Discharges"</i></b>
12:35 – 14:00	Lunch
14:00 – 16:00	<i>Ad hoc</i> sessions and/or free time
16:00 – 18:00	<b>SESSION IV:</b> Poster Session with Afternoon Coffee
18:15 – 20:15	Dinner on William D. Evans (steamship) Be prompt as ship will leave at 18:45

## **WEDNESDAY, MARCH 4, 2009**

- 07:30 – 08:30 Breakfast
- 08:30 – 08:35 Announcements / Session Overview
- 08:35 – 12:35 **SESSION V: SURFACE ENGINEERING AND MATERIALS SYNTHESIS**  
**Session Chair:** S.-J. Park
- 08:35 – 09:05 Michael Thomas  
Fraunhofer Institute for Surface Engineering and Thin Films, Germany  
***“Applications of DBD-Type Cavity Microplasmas for Patterned Surface Treatment or Coating”***
- 09:05 – 09:35 Paul Bryant  
University of Liverpool, UK  
***“Atmospheric Pressure Micro-Cavity Discharge Array Treatment of Hydrophobic Polymers to Generate Hydrophilic Surfaces”***
- 09:35 – 10:05 Yoshiki Shimizu  
National Institute of Industrial Science and Technology, Japan  
***“Application of Atmospheric Pressure, Ultra-High Frequency Microplasma Jet to Preparation and Deposition of Inorganic Nanoparticles”***
- 10:05 – 10:35 Break
- 10:35 – 11:05 Mohan Sankaran  
Case Western Reserve University, USA  
***“Nanotechnological Applications of Microplasmas”***
- 11:05 – 11:35 Ying-Yi Lin  
National Cheng Kung University, Taiwan  
***“Non-Lithographic Fabrication of Surface Enhanced Raman Scattering Substrates Combining Atmospheric Pressure Micro-Plasma Source and Au Nanoparticles”***
- 11:35 – 12:05 Hiroyuki Miyazoe  
University of Tokyo, Japan  
***“Microplasma Assisted Focused Electron Beam Direct Patterning”***
- 12:05 – 12:35 Andrew Marchesseault  
Technical University Braunschweig, Germany  
***“Scale-Up of Dielectric Barrier Discharge Micro-Plasma Stamps for Area Selective Surface Treatment in Biological and Chemical Applications”***
- 12:35 – 13:30 Lunch
- 13:30 – 16:30 *Ad hoc sessions and/or free time*
- 16:30 – 17:00 Coffee Break
- 17:00 – 18:30 **SESSION VI: PHOTONIC DEVICES AND APPLICATIONS**  
**Session Chair:** V. Schulz-von der Gathen
- 17:00 – 17:30 Osamu Sakai  
Kyoto University, Japan  
***“Metamaterials Activated by Microplasmas”***

**WEDNESDAY, MARCH 4, 2009 (continued)**

- |               |   |
|---------------|---|
| 17:30 – 18:00 | Sung-Jin Park<br>Eden Park Illumination, Inc., USA<br><b><i>“Microplasma Lighting: Innovative and Green Solutions for Future Lighting Applications”</i></b> |
| 18:00 – 18:30 | Yong Seog Kim<br>Hongik University, Korea<br><b><i>“Recent Advances In AC-PDPs”</i></b>   |
| 18:30 – 20:00 | Sponsored Reception with <b><i>SESSION VII</i></b> : Poster Session   |
| 20:00 – 22:00 | Dinner  |

## **THURSDAY, MARCH 5, 2009**

- 07:30 – 08:30            Breakfast
- 08:30 – 08:35            Announcements / Session Overview
- 08:30 - 12:05            **SESSION VIII: BIOMEDICAL AND ENVIRONMENTAL APPLICATIONS**  
**Session Chair:** M. J. Kushner
- 08:35 – 09:05            Michael Kong  
Loughborough University, UK  
***“Cold Atmospheric Plasma Jet Arrays: Fundamental Characterization and Treatment of 3D Surgical Instruments”***
- 09:05 – 09:35            Jeffrey Hopwood  
Tufts University  
***“Frequency Scaling of Microplasmas from 450 MHz to 1.9 GHz”***
- 09:35 – 10:05            Graciela Brelles-Mariño  
California State Polytechnic University, USA  
***“Is Gas Discharge Plasma a New Solution to the Old Problem of Biofilm Inactivation?”***
- 10:05 – 10:35            Coffee Break
- 10:35 – 11:05            Alena Hinze  
Technical University Braunschweig, Germany  
***“Microplasma-Based Patterned Amination of Polypropylene-Carbon Composites for the Spot Synthesis of Peptide Libraries”***
- 11:05 – 11:35            Moo-Been Chang  
National Central University, Taiwan  
***“Removal of PFCs from Gas Streams Via Plasma Catalysis”***
- 12:15 – 13:30            Lunch
- 13:30 – 16:30            *Ad hoc* sessions and/or free time
- 16:30 – 17:00            Coffee Break
- 17:00 – 19:00            **SESSION IX: MICROPLASMA CONSORTIA – OVERVIEW AND FUTURE PROSPECTS**  
**Session Chair:** M. Kong
- 17:00 – 17:30            Mark J. Kushner  
University of Michigan, USA  
***“Microplasmas and Physics 2010”***
- 17:30 – 18:00            Jörg Winter  
Ruhr – Universität Bochum, Germany  
***“The Research Group ‘Physics of Microplasmas’ at Ruhr – Universität Bochum”***
- 18:00 – 18:30            Kunihide Tachibana  
Kyoto University, Japan  
***“Report on the MEXT Consortium on Microplasmas in Japan from 2003 to 2008”***

**THURSDAY, MARCH 5, 2009 (continued)**

18:30 – 19:00	James Bradley University of Liverpool, UK <b><i>“Micro-Plasma Science and Technology in the UK: Towards a New Consortium”</i></b>
19:00 – 19:45	Social Hour
19:45	Conference Dinner

**FRIDAY, MARCH 6, 2009**

07:30 – 08:30	Breakfast
08:30 – 08:35	Announcements / Session Overview
08:35 – 12:05	<b>SESSION X: MICROPLASMAS IN LIQUIDS</b> <b><u>Session Chair:</u></b> O. Sakai
08:35 – 09:05	Koichi Yasuoka Tokyo Institute of Technology, Japan <b><i>“Plasma-Water Processes and Electrohydrodynamic Gas Flow Generation Using Micro Plasmas”</i></b>
09:05 – 09:35	Mark Kushner University of Michigan, USA <b><i>“Self-Contained Multiphase Microplasmas: Bubbles in High Pressure Gases and Liquids”</i></b>
09:35 – 10:05	Takaaki Tomai University of Tokyo, Japan <b><i>“Atmospheric Pressure Plasma Generation in Microbubbles Formed in Saline Solution”</i></b>
10:05 – 10:35	Break
10:35 – 11:05	Toshiro Kaneko Tohoku University, Japan <b><i>“Novel Nano-Bio Material Formation Using Gas-Liquid Interfacial Microplasmas”</i></b>
11:05 – 11:35	Naoki Shirai Tokyo Institute of Technology, Japan <b><i>“Atmospheric DC Glow Microdischarges Using Electrolyte Electrodes and Axial Miniature Helium Flows”</i></b>
11:35 – 12:05	Closing Remarks and Future Plans
12:05	Pick up boxed lunch

*Abstracts*

# **Fundamentals and Applications of Microplasmas**

**March 1- 6, 2009**

**Catamaran Resort Hotel, San Diego, California**



**Engineering Conferences International**

## **MICROPLASMAS: FUNDAMENTAL ASPECTS AND FUTURE PROSPECTS**

Ulrich Kogelschatz, Retired from ABB Corporate Research, Baden/Switzerland  
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The major physical processes in atmospheric-pressure microplasmas will be addressed. Different types of microplasmas in free space and in confined geometries will be discussed. The major emphasis will be on the generation of non-equilibrium microplasmas and on their properties. Improved understanding resulted from detailed numerical modeling and from advanced spectroscopic diagnostics. The advantages and disadvantages of DC as well as AC, RF and pulsed operation will be discussed. Possibilities to create large arrays of 2D or 3D microplasmas will be shown.

Microplasmas have already found a number of applications as radiation sources and plasma displays, as plasmachemical microreactors, as sources of excited or ionized species, for the generation of nanoparticles, the modification of surfaces and for pollution control. New applications are emerging in the fields of germ reduction, wound treatment and tissue engineering.



## **ELECTRIC FIELD MEASUREMENT IN HIGH-PRESSURE HYDROGEN MICRODISCHARGES**

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Kazunobu Kobayashi, Osaka University  
Uwe Czarnetzki, Ruhr-University Bochum  
Satoshi Hamaguchi, Osaka University

High pressure discharges have recently attracted much attention as research topics due to their possible application to various industrial processing. Although many interesting application-oriented studies have been extensively performed, it seems only a limited number of reports about their basic discharge diagnostics have been published so far. Electric field is one of the key parameters in discharge dynamics, which we believe should be understood better for the discharge optimization. Electric field induced coherent Raman scattering (E-CRS) measurement is a promising technique for measuring electric field in high-pressure environments. In this study, we have demonstrated electric field measurements in high-pressure hydrogen microdischarge environments by the E-CRS measurement. Two pulsed ns laser beams (532 nm and 683 nm) are employed for the measurements. In hydrogen molecules the two laser beams together with the electric field induce a coherent IR signal at a wavelength of 2.4  $\mu\text{m}$ . The same set-up also produces the normal coherent anti-Stokes Raman scattering (CARS) signal at 436 nm. The ratio of those two signals (IR and CARS) is a function of the electric field strength and is independent of the populations of states involved in the Raman transition, so that electric fields can be estimated by using the ratio even in discharges where the populations can vary. Microdischarges mainly investigated in this study are repetitive (10 kHz) nanosecond-pulsed discharges, generated at 0.3 atm by the two parallel electrodes with the gas distance of about 1.15 mm. The measurement reveals that the initiation of net charge accumulation on an electrode occurs very rapidly without strong light emission. The strong light emission is observed at a few nanosecond later after the large initial charge accumulation. Further details such as field profile evolution will be presented in the conference.

## **SPECTROSCOPY BASED INVESTIGATION OF HEATING MECHANISMS IN MICROSCALE ATMOSPHERIC PRESSURE PLASMA DISCHARGES**

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H. Böttner, J. Winter, Ruhr-Universität Bochum

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The investigation of microplasmas is generally complicated due to access limitations given by their small confining structures. Diagnostics become even more challenging in the collision dominated high pressure regime e.g. on account of collisional de-excitation (quenching). Therefore discharge formation and dynamics of these discharges is only rudimentarily understood. Phase resolved optical emission spectroscopy (PROES) allows the investigation of electronic excitation dynamics often referred to as heating processes inside microplasmas. Limitations of emission spectroscopy only allow access to specific parameters of the discharge. The range of accessible parameters can be extended by a combination of the spectroscopic measurements with numerical simulations resulting in a 'model-based diagnostics'. Here we discuss PROES measurements complemented by numerical fluid simulations on two specific types of microdischarges: a micro scale atmospheric pressure plasma jet ( $\mu$ APPJ) specifically designed for optimum optical access (e.g. for laser diagnostics) and a microdischarge array. The discharge types are complementary in their excitation frequencies (13.56 MHz rf excitation for the  $\mu$ APPJ vs. some ten kHz for the microarray) and their dimensions (1 mm vs. 50  $\mu$ m). We will focus on heating mechanisms determining the various operating modes of the discharges.

## ATMOSPHERIC MICROPLASMA FOR CANCER AND OTHER MICROPLASMAS: MODELINGS AND EXPERIMENTS

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Felipe Iza, Department of Electronic and Electrical Engineering, Loughborough University

Sang Rye Park, Gyoo Cheon Kim, Department of Oral Anatomy, Pusan National University

In our difficult war against cancer for the past few decades, we have emerged out with a drastically novel therapeutic approach with atmospheric pressure plasmas suitable for biomedical applications [1,2,3]. A non-thermal air plasma has shown its effectiveness in killing cancer cells. We have used 30 nm gold nanoparticles and antibody conjugation to selectively enhance the therapeutic effects of the plasma. After the FAK-GNP binds to FAK proteins specifically, irradiation of plasma stimulated gold nanoparticles caused deactivation of FAK, thereby drastically increasing the death rate to 74%, which is five times enhancement compared with the case of plasma alone without antibody-conjugated nano particles. Our study demonstrates that non-thermal plasma can stimulate gold nanoparticles located inside cells to cause cell death even with a low-dose plasma treatment. This research opens the door to a new paradigm where non-thermal plasma and antibody conjugated-gold nanoparticles team up to create a powerful weapon against cancer. Our other atmospheric pressure air, He, or Ar plasma devices for coagulation, sterilization, and tooth whitening are studied experimentally and theoretically.

### References

1. Iza, F., Lee, J. K. & Kong, M. G., Phys. Rev. Lett. 99, 075004 (2007).
2. Iza, F. et al., Plasma Proc. Polym. 5, 322-344 (2008).
3. GC Kim, et al., J. Phys. D : FTC (accepted)

## VOLT-AMPERE CHARACTERISTICS AND DIAGNOSTICS OF MICRO DISCHARGES

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Basic breakdown properties of micro discharges should be scalable to standard size/pressure discharges if the same physics persists. We have studied the breakdown in normal size discharges and have used several scaling laws including  $E/N$ ,  $pd$ ,  $jd^2$  in order to test the main physics defining the discharge. In addition to the breakdown as represented by the Paschen curve we have employed Volt Ampere characteristics to study the properties of the discharge and also the key processes leading to the breakdown as the secondary yield coefficient has a deciding role on the behavior of the operating voltage as current is changed in dc discharges. Theoretical predictions state that the standard Townsend phenomenology breaks down only below 0.005 mm gaps when field emission becomes the key mechanism affecting the breakdown and deforming the left hand side of the Paschen curve. However it has been often observed that the voltage is constant and equal to the minimum breakdown voltage to the left of the minimum and it may be argued either that the long path breakdown becomes important or that some new processes are introduced. Plasma needle also belongs to a group of micro discharges and it operates supplied by rf power. We have tested how volt ampere characteristics may be related to the real power submitted to the discharge, how modes of operation differ in external properties and we have applied mass spectrometry to see how production of chemically active radicals may be associated with different modes of operation.

## **COMPARISON BETWEEN ATMOSPHERIC-PRESSURE MICRODISCHARGES AND LOW-PRESSURE DISCHARGES, FROM AN OES PERSPECTIVE**

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Xi-Ming Zhu, Tsinghua University  
Li-Guo Zhu, Tsinghua University

The characteristics of optical emission spectrum of atmospheric-pressure microdischarges (microwave split-ring resonator, MSRR) are investigated with argon and argon/xenon gases. The relative emission intensities from different excited levels have clear distinctions from those at low pressures. This difference, according to a simple collisional-radiative (C-R) model, is caused by collisions between atoms, which is very strong at atmospheric pressure. As a result, the direct excitation and ionization by electron impact, being dominant at low pressure, becomes less important than the step excitation and Penning ionization at atmospheric pressure. On the other hand, atom-impact population transfer dominates the depopulation mechanisms of excited levels, instead of the radiation processes. By analyzing the excited particle kinetics, one can estimate the electron energy distribution function (EEDF) at atmospheric pressure by using optical emission spectroscopy (OES). A spatially-resolved OES measurement result on MSRR will be reported, from which non-uniform and non-equilibrium EEDF are observed. Its possible mechanism will be discussed.

## **LASER-INDUCED MICROPLASMAS**

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Microplasmas are produced if tightly focused pulsed or continuous wave laser radiation of adequate fluence is interacting with gaseous, liquid or solid matter. Depending on the laser parameters (fluence, wavelength, and pulse length) very tiny, extremely hot plasmas can be generated which easily atomize even refractory samples. In analytical science, the plasma emission, the ions of the plasma, or particles created by the plasma are used for chemical analysis of the matter probed by the laser. In particular, the emission spectroscopy of laser-induced microplasmas, the laser-induced breakdown spectroscopy (LIBS), is a powerful technique with a wide variety of applications. Very recently, it is used for the analysis of airborne and immobilized nanoparticles as well as for thin films and depths analysis of solids. Other prominent features of LIBS are remote measurements of samples in hazardous, harsh and difficult to access environment, such as radioactive material in hot cells, metal melts during production, deep-sea geophysical prospection, or probing the elemental composition of samples on nearby planets (e.g., on Mars).

The paper will give examples of applications, but will also discuss open questions connected with the ablation and plasma production process.

\* The project is a collaborative effort of University of Florida, BAM and ISAS, jointly funded by NSF & DFG.

## **GAS-TEMPERATURE-DEPENDENT GENERATION AND DIAGNOSIS OF CRYOPLASMA USING DIELECTRIC BARRIER DISCHARGE (DBD) MICROPLASMA**

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To achieve desirable plasma conditions for various applications such as material processing, the gas temperature might be one of the most important parameters. However, up to now, there have been few studies on plasmas with a gas temperature between room temperature (RT) and cryogenic temperature, or on their applications. Below RT, phenomenon such as phase transitions in many gases occurs due to the decrease in particle kinetic energy, and it remains to be studied how this decrease in particle kinetic energy below RT would or may affect plasmas and applications using those plasmas. Therefore, in our work, "cryoplasma" with a gas temperature below RT to liquid helium temperature ( $4.2 < T_g < 300$  K) was developed by employing dielectric barrier discharge (DBD) microplasma and studied [1-5].

As the results, the appearance such as discharge pattern, excited species, discharge mode, average electron density and temperature of cryoplasma all showed  $T_g$  dependent transitions through the continuous particle kinetic energy decrease. Especially below around 60 K, the gas temperature which gas density starts to increase rapidly and Van der Waals force is assumed to start affecting the particles, the results changed drastically compared with higher gas temperatures. Specifically, below 60 K, intensities from  $\text{He}_2^+$  were observed. Discharge mode changed from atmospheric glow to atmospheric Townsend discharge mode. Then finally, the average electron density increased from  $10^9$  to  $10^{11} \text{ cm}^{-3}$  whereas electron temperature of cryoplasma decreased from approximately 13 to 2 eV. The increase of  $\text{He}_2^+$  is showing the first step toward clusterization of plasma species and this is somewhat similar to the initial stage of the phase transition from gas to liquid state, meaning the possibility of phase transition in cryoplasma. Moreover, decrease in electron coupling parameter also shows the effect of Coulomb force in cryoplasma. Details will be presented at the conference.

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## MICROPLASMA DISCHARGES IN POLYMER FOAMS: A NEW ROAD TO FLEXIBLE PIEZOELECTRIC POLYMER FILMS

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In recent years, polymer foams with embedded space charges (so-called ferroelectrets) have received considerable attention due to their high piezoelectric activity combined with a high mechanical flexibility and compliance. The piezoelectric effect results from dipoles consisting of electrical charges generated in a dielectric barrier discharge (DBD) and trapped at the internal surfaces of the gas-filled voids. To help understanding the creation, deposition and storage of these charges in air-filled cavities with sizes in the 1...20  $\mu\text{m}$  range, samples of cellular polypropylene (PP) films were subjected to high electric fields (ramped up and down at rates of approximately  $15 \text{ MV m}^{-1} \text{ s}^{-1}$  while their light emission and piezoelectric activity was monitored.

Time-resolved images obtained with an EMCCD photon-counting camera show discharge processes in individual voids. A spectroscopic study of the microplasma discharges revealed electronically excited  $\text{N}_2$  molecules and  $\text{N}_2^+$  molecular ions. The vibronic band strengths indicate an internal electric field of approx. 25 MV/m, consistent with Townsend's model of Paschen breakdown. There is a strong correlation between the emitted light and the piezoelectric  $d_{33}$  coefficient.

When the external electric field is reduced back to zero after completion of the charging process, the field built up by the deposited charges triggers a back discharge, thus destroying up to 75% of the piezoelectric activity. Suppressing the back discharge could provide a pathway to a significantly enhanced piezoelectric activity.



## **MICRODISCHARGES AND THE GENERATION OF STABLE, LARGER-VOLUME, HIGH-PRESSURE DC PLASMAS**

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In a collaboration with the colleagues listed below, models of microdischarges in different configurations have been developed and detailed comparisons have been carried out with companion experiments from different laboratories in France. The configurations discussed in this talk include microhollow cathode, microcathode sustained, and cathode boundary layer discharges (following the terminology of Schoenbach). After a brief summary of the models, I will present results of our work on microcathode sustained discharges and summarize our more recent modelling results in the cathode boundary layer configuration.

Microcathode sustained discharges occur between a microhollow cathode discharge and a third electrode, placed some distance away and biased positively. In this configuration, a non-thermal plasma can be generated and maintained in a relatively large volume; that is, for  $pd$  (pressure  $\times$  distance) products up to 760 torr cm and more. Breakdown occurs at small  $pd$ , between the closely spaced electrodes in the microhollow cathode. Then, for suitably chosen values of discharge current, gas pressure, and position and bias on the third electrode, a conducting channel (similar to a positive column) forms in the larger volume between the microhollow cathode and the third electrode. Over a range of values of bias voltage, the discharge is quite stable and the current on the third electrode is controlled by the cathode current (the microdischarge). Plasma properties in the 'positive column' have been calculated and compared with experiment, as will be described.

The cathode boundary layer is another configuration with potential for generating larger-volume plasmas. In this configuration, a central hole is drilled through the anode and dielectric - but not through the cathode - of an anode/dielectric/cathode sandwich. The sandwich thickness is some 100s of microns. Because the cathode surface available to the discharge is limited in this configuration, the voltage-current characteristic becomes positive and operating arrays of such discharges without the need for individual ballasts may be possible. I will summarize our recent modelling results in this configuration and more detail will be provided in a poster.

Acknowledgement: The modelling work was carried out in collaboration with JP Boeuf, G Hagelaar, K Makasheva, and E. Munoz-Serrano, and companion experiments were performed by V. Puech, J. Santos Sousa, N. Sadeghi, X. Aubert, and A. Rousseau. This work was supported by ANR, the French National Research Agency.

## **APPLICATION OF MICROPLASMA FOR FLEXIBLE DISPLAY DEVICES**

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Recently, microplasma has been the focus of attention for various applications and is in particular considered an attractive candidate technology for realizing future flexible displays. In this work, microplasma was applied to flexible display devices and an adequate sustain margin and flexibility were demonstrated. In addition, microplasma generated in flexible display devices was characterized in terms of reliability in accordance with various materials. From the results, the microplasma showed feasibility for application in future flexible display devices.

## **ATMOSPHERIC PRESSURE PLASMA MICRO JET**

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A single opening micro-hollow cathode discharge is generated at atmospheric pressure between a cathode with sub-millimeter opening and a perforated anode (separated by a distance of 0.5 mm). When the operating gas (e.g. air or nitrogen) is pushed through the opening of this structure and dc power is applied, a spatially well-defined atmospheric-pressure plasma micro jet (PMJ) can be sustained in ambient air as well as in a quasi-steady gas cavity within liquid media. Typical operating parameters of the PMJ are gas flow rate of ~3 SLM, discharge current of 20-30 mA, discharge voltage of 400-600 V, respectively. Although the temperature at the discharge zone can reach hundreds of  $^{\circ}\text{C}$ , at a distance of 1 cm away from the exit nozzle, gas temperature is around 40  $^{\circ}\text{C}$ . PMJ is found to inactivate bacteria effectively in air as well in water. Possible pathway of the inactivation will be briefly discussed. With the assistance of hydrogen peroxide, PMJ is also effective in teeth bleaching. This might open another door for many recently developed atmospheric pressure non-thermal plasma torches.

## VARIOUS MICROPLASMA JETS AND THEIR APPLICATION TO STERILIZATION

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Fabrications and properties of various microplasma jets including coplanar-electrodes device, hollow-electrodes device, twin injection-needle device, jet from a flexible tube, and pencil-type electrode will be discussed. The twin plasma columns in the twin injection-needle device are regarded as skinny rods with a uniform charge distribution, and the change of the plasma column lengths with different distances between the plasmas is compared with the change of the capacitance of the skinny rods presented as a model. The pencil-type configuration produces a long cold plasma jet capable of reaching 3.5 cm and having various excited plasma species shown through optical emission spectrum. By introducing an appropriate gas flow rate, striated discharge patterns in the plasma jet from the pencil-type configuration are produced through ionization wave propagation. Argon plasma jets penetrate deep into ambient air and create a path for oxygen radicals to sterilize microbes. A sterilization experiment with bacterial endospores indicates that an argon-oxygen plasma jet very effectively kills endospores of *Bacillus atrophaeus* (ATCC 9372), thereby demonstrating its capability to clean surfaces and its usefulness for reinstating contaminated equipment as free from toxic biological agents.

## **LOW FREQUENCY (LF) MICROPLASMA JET AND ITS APPLICATION TO PLASMA INDUCED CHEMICAL PROCESSES IN LIQUIDS**

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Recent development of low temperature atmospheric plasmas has enabled non-conventional plasma processing. In this paper, discharge mechanisms and applications of non-thermal microplasma jets are discussed. Low gas temperature atmospheric pressure plasmas can be produced by a high-voltage (HV) low-frequency (LF) power supply in the range of kV and kHz in a tube where a discharge gas (typically He or Ar) flows. We call it a LF microplasma jet as the plasma seemingly extends from the tip of the tube into the ambient air. Partial discharges between the HV electrode and the electrical ground in the surroundings occur in the He/Ar gas flowing into the air. Observation by a high speed ICCD camera has shown that two different types of discharges take place during the rising and falling phases of the applied HV. Due to the low gas temperature, such non-thermal plasma jets may be suitable for damage-free plasma processing in liquids. While atmospheric pressure plasmas generated by arc or streamer discharges often increase the gas temperatures, nonthermal plasma jets with low temperatures have the advantage of being able to treat soft materials such as solutes in liquids, organic materials, and living organisms without extensive damages. Though ions of plasma play an important role as energy carriers in conventional low-pressure plasmas processing, energetic electrons of plasmas that generate free radicals are thought to be essential in plasma processing in liquids. Non-thermal plasmas in contact with a liquid can cause complex reactions in the liquid phase, including reduction, polymerization and sterilization. To determine the cause of such chemical reactions in liquids, we have identified some free radicals formed in aqueous solutions after the plasma exposure using electron spin resonance (ESR) with spin-trapping agents. From optical emission spectroscopy (OES), several free radical species were also identified in the gas phase. Free radicals that have sufficiently long lifetime in the liquid phase and therefore can diffuse into the liquid bulk can cause chemical reactions away from the gas-liquid interface.

## ANALYSIS OF MICROPLASMA JETS BY MEANS OF MOLECULAR BEAM MASS SPECTROMETRY

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The analysis of microplasma discharges operated at atmospheric pressures is a challenging task due to their small dimensions and high pressure. Especially the detection of reactive low density plasma chemistry products is very difficult. One possible way, how to gain more knowledge about the densities of these products is a molecular beam mass spectrometry (MBMS). In this technique, plasma is sampled to a mass spectrometer in a triply differentially pumped housing and the species densities in the formed molecular beam are measured. The densities in the microplasma can then be quantified, if possible composition distortions appearing in the molecular beam are considered. An important issue in MBMS is the level of background pressures in the pumping stages. These pressures have to be low enough to prevent any disturbance of the molecular beam. This condition sets bounds to e.g. the size of the sampling orifice and imposes high demands on the pumping speed in the first pumping stage. The beam-to-background density ratio in the ionizer of the mass spectrometer is then typically close to unity. To improve the performance and sensitivity of the MBMS we have constructed a triple differential pumping stage with a rotating skimmer within the first pumping stage, which serves effectively as a valve separating periodically the vacuum system from the ambient environment. The time-averaged particle flux into the mass spectrometer is effectively reduced; however, the density in the molecular beam remains the same during the time period when the sampling orifice is open. An excellent beam-to-background ratio of 14 and a detection limit below 1 ppm are achieved in this way. The measurements of ozone and atomic oxygen in He/O<sub>2</sub> microplasma jet and the analysis of Ar/HMDSO microplasma jet used for SiO<sub>x</sub> deposition will be presented.

## **DESIGN OF A MINIATURE MICROWAVE PLASMA TORCH AND ITS OPERATION IN PLASMA-ASSISTED COMBUSTION AND MICROWAVE-POWERED DISCHARGE-ONLY MODES**

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A miniature microwave plasma torch for operation at atmospheric pressure is designed and operated in two modes including a microwave-powered discharge-only mode and a plasma-assisted combustion mode. The torch is based on a discharge or flame formed at the open end of a coaxial structure where the feed gas flows through an orifice in the end of the center conductor. The coaxial torch structure is powered with 2.45 GHz microwave energy. When the torch is operated in the discharge-only mode using argon gas, a plasma discharge from 0.3 - 1 mm in diameter with a length from 2 - 4.5 mm is produced. The torch requires a relatively low input microwave power of 8 – 115 W to create the discharge. The maximum discharge volume of 2.5 cubic mm and the minimum absorbed power density of 5 W/cubic-mm are observed at 250 sccm flow rate using argon as the feedgas. Based on the optical emission spectroscopy measurements of a nitrogen (1.5%) and argon gas mixture, the plasma gas temperature measured is in the range of 1200 K to 1900 K for microwave absorbed power levels of 18 to 115 W, respectively. When the miniature torch is operated in the plasma-assisted combustion mode using methane and oxygen as the feed gases, a premixed flame is produced. The addition of less than 30 W of microwave power to a combustion flame serves to alter the premixed combustion flame and extends the fuel lean burning limits, increases the flame length and intensity, and increases the number density and mixture of excited radical species in the flame vicinity. The flame/discharge gas temperature also increases. Additional characteristics of the torch and potential applications will be discussed in the presentation.

## **MICROPLASMA JET FOR MEDICAL APPLICATIONS**

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Cold microplasma jets, which can be operated at atmospheric pressure into air have shown remarkable potential for medical applications, such as the sterilization of heat sensitive materials or as therapeutic agent to promote wound healing. With multiple interaction mechanisms between reactive agents and living cells, plasma treatments can also offer an alternative method against many other diseases and conditions, in particular of the skin, that generally require the prescription of antibiotics or other systemic medications.

We were successful in generating a plasma (afterglow) jet in a microhollow cathode geometry, which is operated with a dc voltage and at atmospheric pressure with and into ambient air. By flowing air through the discharge channel at a rate of about 7 Ltr/min a 10-20 mm long plume is observed. The temperature in this expelled afterglow plasma reaches values that are close to room temperature at a distance of 5 mm from the discharge origin. Emission spectra show that atomic oxygen, hydroxyl ions and various nitrogen compounds are generated in the discharge and are driven out with the gas flow.

We have investigated the effectiveness of this microplasma jet against notoriously difficult to treat yeast infections. In an in vitro study, complete eradication of candida kefyr (a model for candida albicans ?the most common yeast infection) could be achieved with an exposure of 90 seconds at a distance of 5 mm. Other pathogens that were tested, such as E.coli and a matching E.coli strain-specific virus, OX174 (a bacteriophage), also respond well. The safety of the treatment was studied by an in vivo skin model. The exposure of healthy skin to the plasma jet, when using the same treatment parameters as for the in vitro studies, and even a treatment with a ten times higher dose, did not result in any damage.



## **PLASMA BULLETS IN CYLINDRICAL DBDS AND PIEZO-ELECTRIC SURFACE DISCHARGES**

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Certain types of surface discharges may produce plasma jets, i.e. elongated light emitting plasma zones extending some centimeters downstream from the electrodes. Although the jet looks stationary to the eye, short-exposure imaging reveals that the plasma consists of small fast-moving bullet-like structures which can be precisely triggered by the excitation voltage. A very similar phenomenon has recently been observed in a novel piezo-electric discharge. Here the high electric fields necessary for plasma excitation are generated by a modified piezo-electric transformer. The "plasma bullets" are regarded as ionization waves. Similarities and differences between the two types of discharges are discussed.

## APPLICATIONS OF DBD-TYPE CAVITY MICROPLASMAS FOR PATTERNED SURFACE TREATMENT OR COATING

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For biomedical and electronic applications like biosensors, flexible printed circuits, RFID antennas and MEMS, patterned surfaces manufactured by subtractive processes based on lithography, etching, or laser ablation are well established. Due to better cost and resource efficiency new additive processes have been developed using mostly different printing technologies. A novel patterning technology based on plasma functionalization or coating is the so-called *plasma printing* process at atmospheric pressure, which will be presented in this paper. Here, microcavities with structure widths down to 10  $\mu\text{m}$  are formed temporarily by contacting a substrate with a suitably designed *plasma stamp*. Inside these microcavities partial discharges, special cases of dielectric barrier discharges (DBDs), can be ignited for surface coating and modification processes in a similar way as already demonstrated for common DBD arrangements.

Depending on the application field, various adapted set-ups of the plasma printing technology are possible. For surface functionalization of even non-flexible materials, like glass, wafers or thicker polymer sheets, flat metallic or dielectric stamps with closed cavities were used. Area-selective hydrophilic properties can so be achieved by plasma activation. Using nitrogen-containing atmospheres more than 10 primary amino groups per  $\text{nm}^2$  can be introduced into polyolefine surfaces, as determined using  $\text{NH}_2$ -selective chemical derivatization (CD) combined with quantitative ATR-FTIR spectroscopy.

For a micropatterned deposition of coatings exceeding a thickness of a few nanometers, the numbers of precursor molecules contained inside closed cavities are generally not sufficient. Therefore it is necessary to supply gases consumed during film deposition continuously into the plasma cavities. This can be achieved in two ways: (i) Using a complex network of gas channels on the backside of the cavities or (ii) with plasma stamps based on a porous material with cavities on its front side. With these technologies patterned surfaces coating with different monomers, e.g. aminopropyl-trimethoxysilane, glycidylmethacrylate or acetylene, has successfully been demonstrated for structure widths down to 50  $\mu\text{m}$ .

The latest development is the continuous patterned treatment of polymer foils in a reel-to-reel process. In this case the microcavities are formed by rotogravure on a print roller. Using a special adapted counter electrode a long-term stable microstructured plasma activation of different polymeric substrates can be achieved. With a mixture of  $\text{N}_2$  and  $\text{H}_2$  as a process gas a continuous patterned surface amination without roughening of the polymer surface is possible. The combination of this plasma process with electroless copper metallization leads to a fast and highly efficient process for the manufacture of structured metallizations for flexible printed circuits or RFID antennas.

## ATMOSPHERIC PRESSURE MICRO-CAVITY DISCHARGE ARRAY TREATMENT OF HYDROPHOBIC POLYMERS TO GENERATE HYDROPHILIC SURFACES

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Polymers are an important material for technological and biological applications (such as spatial confinement of cells) because of their flexibility for fabrication, low density and low manufacturing cost [1]. One drawback is their hydrophobicity which is usually overcome by chemical or low pressure plasma treatment. Here, a silicon based micro-cavity discharge array [2] was operated in neon at atmospheric pressure to generate hydrophilic polystyrene (PS), fluorinated ethylene-propylene co-polymer (FEP) and polytetrafluoroethylene (PTFE) polymer surfaces. X-ray photoelectron spectroscopy (XPS) was used to study changes in the polymer surface functionality with discharge exposure and the treatment depth (by using the O 1s /O 2s ratio). The influence of the driving frequency, treatment time and the sample-to-array distance on the surface hydrophilicity (determined by water contact angle measurements) was also investigated. It was found that increasing the driving frequency (from 5 – 20 kHz), the treatment time (from 5 s to 45 minutes) and decreasing the sample-array distance (from 16 to 1.2 mm) all led to a significant decrease in the measured water contact angle. This decrease was greatest for PS where ~ 80° was obtained. For both FEP and PTFE the decrease was significantly smaller being 25 - 30°. After treatment the hydrophilicity degraded, due to the aging effect, but became stable after two days (PS settled within 35° of the untreated value). None of the polymers reverted back to their original hydrophobic state. XPS analysis of the treated PS surfaces showed that a significant amount of oxygen (increase from ~ 1 at.% to 12 at.%) had been incorporated into the surface layer. Correspondingly, the carbon surface concentration decreased from approximately 99 at.% to 86 at.%. Oxygen incorporation and subsequent generation of new oxygen surface groups was found to be uniform across the sample surface. The O 1s /O 2s ratio, of around 2.3, indicates the oxygen rich layer to be less than 10 nm thick. Possible mechanisms for surface modification are discussed.

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## APPLICATION OF ATMOSPHERIC-PRESSURE ULTRA-HIGH-FREQUENCY MICROPLASMA JET TO PREPARATION AND DEPOSITION OF INORGANIC NANOPARTICLES

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We are developing a wire-spraying technique using an atmospheric-pressure microplasma jet (APMPJ) driven with an ultra-high-frequency (UHF), in which nanoparticles (NPs) are formed by condensation of the evaporants or solidification of the droplets, derived from the wire source material. In the past a few years, we studied primarily the following topics related to wire spraying using the APMPJ. (1) Development of metal-deposition methods in ambient air. (2) Generation of room-temperature  $H_2/Ar$ -APMPJ and its application to NP preparation. In this paper, we mainly present these topics.

### (1) Development of metal-deposition methods in ambient air.

In the deposition of metal NPs such as tungsten and molybdenum, the microplasma was generated by Ar gas mixed with  $H_2$  (below the lower explosion limit of  $H_2$  in air) and continuous-wave UHF.  $H_2$  introduction facilitated the evaporation of the wire source material (tungsten and molybdenum wire) and was effective to prevent the oxidation of the deposit during the processing performed in ambient air. Actually, the deposit obtained was mostly composed of metal NPs. In molybdenum deposition, there were two findings. (a) The crystal structure of the particles was face-centered cubic (fcc) structure, which is a metastable structure of Mo and normally obtained at high pressure above 6 Mbar. (b) The constituent grains had a unique five-fold symmetrical structure like a star and grew preferentially along the five-fold axis.

### (2) Generation of room-temperature $H_2/Ar$ -APMPJ and its application to gold NP preparation.

The  $H_2/Ar$ -APMPJ employing continuous-wave UHF, as mentioned above, cannot be applied to preparation of the NPs of noble metals and low-melting point materials such as tin, because their source material wires were instantly melted due to the high gas temperature. To lower the gas temperature for effective preparation of their NPs, we changed the manner of applying UHF from continuous to a pulse-modulated wave. By adopting this change and studying an appropriate waveform of pulsed UHF, we were able to reduce time-averaged gas temperature of  $H_2/Ar$ -APMPJ to room temperature due to decreasing time-averaged input power, to efficiently prepare gold (Au) NPs, and to subsequently deposit them even on non-heat-resistant materials. The AuNPs could be deposited as they were (NP form) on a substrate at a greater interval (more than 5 mm), while they could be locally deposited as tiny film at a shorter interval (2 to 3 mm).

## NANOTECHNOLOGICAL APPLICATIONS OF MICROPLASMAS

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Plasma processing is a well-established technology used in the microelectronics industry for integrated circuit (IC) manufacturing. As the critical dimension of ICs, the length of the gate, continues to shrink, new challenges have arisen for plasma processing of materials. For example, advanced electronic devices will incorporate nanoscale components such as nanotubes, nanowires, and nanoparticles that must be fabricated without photolithographic masks. In addition, new areas have emerged in sensors, energy, and medicine that will make it necessary for plasma processing to merge with nanotechnological applications. In this talk, microplasmas will be presented as an economical, scalable, versatile tool for the synthesis of nanoparticles and other nanoscale materials.

Microplasmas are miniaturized versions of glow discharges that operate stably at atmospheric pressure and contain large concentrations of energetic electrons ( $1\text{--}10\text{ eV}$ ). They are normally formed with direct-current power between a hollow electrode and a counterelectrode such as a mesh. The salient features of the source, small size ( $< 1\text{ mm}$ ) and high-pressure operation, allow various applications in materials synthesis including non-lithographic surface modification [1], gas-phase synthesis of nanoparticles [2], catalytic growth of one-dimensional nanostructures [3], and plasma-electrochemistry [4]. We will discuss these applications in detail and highlight both materials synthesis and characterization.

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## **NON-LITHOGRAPHIC FABRICATION OF SURFACE ENHANCED RAMAN SCATTERING SUBSTRATES COMBINING ATMOSPHERIC-PRESSURE MICRO-PLASMA SOURCE AND AU NANO-PARTICLES**

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Raman spectrum provides high informational content on the chemical structure of the probed substances, which makes this method a very promising tool in biomedical spectroscopy. In particular, nanostructures play a significant role on surface enhanced Raman scattering (SERS). Most investigations utilize lithographic technique as a micro-scale process that leads to an additional cost of wastewater treatment. Micro-plasma technique, with the advantages of e.g., localized processing and reduced implementation costs and low working temperature, provides an ideal option for the fabrication step as a large variety of radicals and nano-aggregates instead of other methods. In this study, we present a method that may generate graphic nano-particles patterns on atmospheric micro-plasma exposed surfaces and thereafter be relevant to the applications of SERS. This process combines the benefits of plasma environment with the enhanced effect of nano-particles. In the experiment, RF-induced argon plasma is employed. Argon plasma, which is chosen for its inertness, is produced at the end of a nozzle and formed by an interaction with a high electrical field. The 100 nm Au/10 nm Ti/Si substrate is initially Raman-inactive and used as the reference. A stage directed by a pair of numerically controlled stepping motors is designed for movements in the x and y directions, which is used to let the plasma jet process on the designed chip. After micro-plasma exposure, Au nano-particles solution is dropped on the substrate. Au nano-particles are anticipated to deposit on the area treated by micro-plasma through a hydrophilic characteristic. A Raman-active molecular probe, 5, 5'-Dithio-bis (2-nitrobenzoic acid) (DTNB), is particularly grafted on the treated substrate to verify an enhanced Raman Effect. The result exhibits a significant SERS enhancement by means of nano-aggregation of Au nano-particles on the plasma exposure surface.

## MICROPLASMA ASSISTED FOCUSED ELECTRON BEAM DIRECT PATTERNING

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Among direct nanopatterning techniques, focused electron beam-induced deposition (FEBID) is a versatile gas-assisted deposition process, which is suitable for the fabrication of 3 dimensional nanostructures [1]. In FEBID, precursor molecules adsorbed on a substrate surface are decomposed into solid nanostructures by the stimulation of electron bombardment with a production of volatile by-products. The deposition of various metallic nanostructures has been strongly investigated for the application to nano-device prototyping, repair of lithography masks and the fabrication of supertips for scanning probe microscopes. Recently, a nicely aligned array of carbon containing tungsten nanodots was fabricated with an average size as small as 1 nm. However, in spite of such advantages, FEBID process still has some drawbacks. One of the most serious problems is the metallic content of the deposits from metalorganic precursors, due to the low reactivity of the process.

In this work, an H<sub>2</sub>-Ar ultrahigh frequency (UHF; 450 MHz) microplasma, which was characterized to be a high-flux plasma source [2], was employed during the FEBI-copper deposition process in order to enhance the reactivity of the process and therefore to obtain deposits with higher metallic content by reducing unwanted carbonaceous impurities. Low-power generation of our UHF microplasma enabled us to reduce the effect of the electromagnetic field from the plasma system on in situ focusing and positioning of the FEB. Conical deposits with sizes comparable to those prepared by the conventional FEBID method were obtained, proving the effective shielding of the electromagnetic field. The atomic content of copper in the plasma assisted-deposit became 3.6 times higher (from 12% to 41%) than that of unassisted one at room temperature. This combination of microplasma and FEB investigated in this work opened application windows for assistance of other direct-write nanomanufacturing processes using focused charged particle beams such as focused ion beam milling and deposition.

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## **SCALE-UP OF DIELECTRIC BARRIER DISCHARGE MICRO-PLASMA STAMPS FOR AREA SELECTIVE SURFACE TREATMENT IN BIOLOGICAL AND CHEMICAL APPLICATIONS**

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Due to their geometric flexibility and effective area-selective surface treatment, densely structured micro-plasma stamps have become attractive tools for use in biological and chemical applications. The increase in overall area usage in such applications has also lead to a requirement for larger stamps that still have the benefits afforded by micro-structuring. In recent works, we reported on micro-plasma stamp designs based on the principle of dielectric barrier discharges and their fabrication. Previous experience includes research into soft-lithographic based designs with dimensions of 3.6 x 3.6 cm and having electrode diameters of 2 cm. Fabrication of these stamps from polydimethylsiloxane (PDMS) has allowed a formable design that is able to seal against many substrates. These stamps have been characterized in detail and optimized with respect to their ignition voltage and the homogeneity of surface treatment. The original application of these micro-plasma stamps for area-selective surface treatment has been presented. The goal of this work has been the application of micro-plasma stamps for the area-selective surface treatment for biological assays as well as the electro-less deposition of nickel. Scale-up based on the results from the optimization has been conducted to enable the treatment of larger areas and with it enlarge the range of applications. Area-selective electro-less deposition of nickel has been conducted on biaxially oriented polypropylene (BoPP) substrates, whereby nickel is deposited only on plasma-activated areas. Miniaturized bio-assays have also been able to take advantage of this treatment for selective surface chemistry, which has enabled the synthesis of molecular probes using innovative designs of probe-arrays for increased through-put and reduced assay time. Area-selective surface treatment by micro-plasma stamps has been used successfully to allow electro-less deposition of nickel onto BoPP substrates, as well as provide the surface chemistry needed for the synthesis of probe molecules to carry out biological assays on the treated substrates. In addition, current research has involved scaling up previous designs to a large electrode diameter of 8 cm. This value is intended to approach the maximum feasible size for 4" (10.16 cm) wafer technology. Cavity density has been developed with spacing as small as 360  $\mu\text{m}$  and cavity diameters as small as 500  $\mu\text{m}$ . Two designs have been introduced, including an x-y array with over 3,800 cavities, as well as a spiral design with nearly 10,000. Initial plasma ignition of the scaled-up design was also successful and further investigations are planned that will make use of an even higher number of cavities. These future stamps will be tested by project partners for their application purposes.



## **METAMATERIALS ACTIVATED BY MICROPLASMAS**

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A microplasma, which has a size smaller than several millimeters, can be inserted into an electronic or optical device to play a major role. Here we design metamaterials composed of microplasmas, where 'metamaterials' have periodic microstructure and show unusual parameters for electromagnetic waves. Since permittivity of microplasmas is less than unity and even negative when the wave frequency is less than their electron plasma frequency, they can change permittivity of metamaterials; metamaterials become active and dynamic by tuning external electric power for microplasma generation.

One of the examples of the metamaterials activated by microplasmas is an array of double-helix metal wires immersed in microplasmas; the double-helix structure makes permeability negative and the microplasmas makes permittivity negative. As a result, the macroscopic refractive index of the array becomes negative. Another example is a perforated metal plate whose holes are occupied by microplasmas; the extraordinary-transmittance spectrum through the perforated metal plate can be controlled by generation of microplasmas. Thanks to the progress of microplasma technology and the variety of metamaterial structure, further novel functions of such metamaterials can be expected in the near future.

## **MICROPLASMA LIGHTING: INNOVATIVE AND GREEN SOLUTION FOR FUTURE LIGHTING APPLICATIONS**

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Recently, demands for the next generation lighting sources having higher efficiency and a low carbon footprint has soared. To that end, Eden Park Illumination, Inc. has, over the past two years, pursued the development and commercialization of microplasma arrays capable of producing visible emission with high luminous efficacy. Technology originally demonstrated in the Laboratory for Optical Physics and Engineering at the University of Illinois has recently advanced to the point of yield thin planar lamps having active areas of at least  $200\text{ cm}^2$  and producing a white luminance above  $10000\text{ cd/m}^2$ .

This new lighting technology is lightweight, below a few mm in thickness, and offers considerable versatility with respect to form factor. In addition to producing light levels, suitable for illumination applications, microplasma arrays provide an environment-friendly, mercury-free lighting source having an expected lifetime of tens of thousands of hours. The technical development of flat lights sources based on microplasma technology and the roadmap for future efforts will be presented.

## RECENT ADVANCES IN AC-PDPS

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Discharge efficiency and power consumption of AC-PDP have been improved almost by a factor of 20 since its commercialization. Still, further enhancements in luminous efficiency are required as the competition becomes more intense with TFT-LCDs in the market. Various approaches to improve luminous efficacy of the dielectric barrier discharges of AC-PDPs have been attempted in the commercial AC-PDPs, which include high Xe-content discharge gases, secondary electron emission materials with smaller band gap energy, electrode and discharge cell designs, and new dielectric materials. In this presentation, advances made in those research areas will be reviewed. In addition, recent research efforts to understand and control the statistical nature of glow discharge ignition are going to be introduced. The statistical variation of discharge ignition is crucial for picture quality as well as price of AC-PDPs and has been reduced enough to drive full HD resolution displays with a single scan driving scheme. Finally, attempts to expand the applications of AC-PDPs will be reported. Especially, the possibilities of transparent AC-PDPs for window displays and flexible AC-PDPs for large area displays will be introduced in more details.

## **COLD ATMOSPHERIC PLASMA JET ARRAYS: FUNDAMENTAL CHARACTERIZATION AND TREATMENT OF 3D SURGICAL INSTRUMENTS**

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Atmospheric microplasma arrays pioneered by Eden's group at Illinois tend to have each discharge confined to small spaces of sub-millimeter scales. This is useful for maximizing electron density – a primary consideration for optical applications. For treatment of uneven surfaces, it is important that reaction plasma species are delivered in abundance to the sample surface. This favors a plasma jet configuration with which plasma production is confined in the upstream region and chemically reactive species are transported to a downstream sample of potentially 3D surface. This talk reports electrical and optical characteristics of a 10-channel atmospheric pressure glow discharge jet array. With an excitation frequency in 10 – 30 kHz, parallel operation of the APGD jet array is found possible only when each jet being individually ballasted. Challenged with sloped plastic plate of up to 15o (as a sample), spatially resolved nanosecond imaging shows that all constituent plasmas in the APGD jet array are fired simultaneously. Jet-to-jet uniformity is studied using both nanosecond imaging and jet-specific current measurement. Variation in the optical intensity of the jet array on the surface of a 15o-sloped substrate is about 12%, a factor of 4 less than that of a single jet scanning over the same substrate. In addition, spatially resolved optical emission spectroscopy is used to obtain spatial variation of atomic oxygen emission lines at 777 and 844 nm. Our results suggest that the APGD jet array is capable of delivering an array of reactive plasma species with very modest spatial variation even when the substrate is sloped at 15o. Their practical applications to sterilization of surgical instruments is illustrated with data of treating surgical forceps, confirming a clear potential of such APGD jet array for both surgical instrument sterilization and other surface processing applications.

## FREQUENCY SCALING OF MICROPLASMA FROM 450 MHZ TO 1.8 GHZ

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Capacitively coupled microplasma generation becomes more efficient at microwave frequencies. Inert gas microplasmas are characterized using excitation frequencies of 450 MHz to 1.8 GHz. These microplasmas are tested at both 1 atm and 0.5 mbar. The microplasma is generated in a 200 micron-wide gap formed in a ring-shaped microstrip transmission line. When operated in resonance, a large microwave potential forms across the discharge gap and generates a microplasma. The radius of the so-called *split-ring resonator* is scaled from 20 mm down to 5 mm as the resonance frequency is increased from 0.45 GHz to 1.8 GHz.

We have measured electrical impedance of these microplasmas, which consists of bulk plasma resistance and capacitive sheath reactance. The plasma resistance is inversely proportional to electron density. These two parameters were found by fitting an expression for the theoretical power reflection coefficient to the experimental forward and reflected microwave power as a function of frequency. The microplasma resistance decreases with increasing frequency, showing that the generation of free electrons depends on the driving frequency. In addition, the reactive sheath impedance and the microwave electrode voltage also decrease with an increase of frequency.

A three-dimensional microplasma simulation shows that a narrower sheath width exists for higher frequency microplasma and this is responsible for reducing the reactive impedance and the peak-to-peak electrode voltage. At higher microwave frequency, the decreased electrode voltage reduces both the plasma potential and the ion kinetic energy losses, thus increasing the electron density.

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## PLASMA-ASSISTED BIOFILM INACTIVATION: A NEW SOLUTION TO AN OLD PROBLEM?

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Biofilms are microbial communities embedded in a matrix mostly composed of exopolysaccharides together with some proteins and nucleic acids. Conventional methods of controlling microbial growth, such as sterilization or disinfection, are often ineffective with these ubiquitous, hard-to-destroy communities. The use of gas discharge plasmas represents an alternative method since plasmas contain a mixture of reactive species and UV radiation whose decontamination potential for free-living microorganisms is well established.

In this study, biofilms were produced using *Chromobacterium violaceum*, a gram-negative bacterium commonly present in soil and water and used in this study as a novel organism. Biofilms were subjected to an atmospheric pressure plasma jet for different exposure times. Our results show that 99.6% of culturable cells are inactivated after a 5-minute treatment. The survivor curve shows a double-slope kinetics with a rapid initial decline in the number of colony-forming units (CFUs) per milliliter followed by a much slower decline with D-values that are longer than for the inactivation of free-living, planktonic organisms, suggesting a more complex inactivation mechanisms for biofilms. Physiological and metabolic determinations together with atomic force microscopy and fluorescence microscopy show that non-culturable cells are still alive after short plasma exposure times.

These results show that bacterial biofilms can be inactivated by using gas discharge plasma and indicate the potentiality of plasma as an alternative sterilization/decontamination method. However, the results also indicate that viability experiments should always be carried out before drawing the conclusion that plasma is useful to kill cells based solely on measurement of culturable cells.

## **MICROPLASMA-BASED PATTERNED AMINATION OF POLYPROPYLENE-CARBON COMPOSITES FOR THE SPOT SYNTHESIS OF PEPTIDE LIBRARIES**

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This paper is aimed to present the use of area-selective plasma-functionalization of carbon-filled polypropylene (PP/C204) minidisks to manufacture micro-arrays with peptide libraries utilizing parallel combinatorial chemical synthesis (also known as SPOT synthesis). Since a few years the introduction of primary amines to polymer surfaces by N- or N,H-containing discharges has gained a growing interest as a novel process tool to provide reactive surfaces for biomedical applications. This kind of microplasma treatment enables a relatively simple and cost effective way to modify the surface properties of compact-disc-shaped polymer wafers generating chemically reactive, hydrophilic anchor spots with dimensions down to a few 100  $\mu\text{m}$  on a hydrophobic background. Compact arrays with hundreds or even thousands of spots can be easily prepared for spatially addressable chemical array synthesis and subsequent in situ detection of biomolecules captured on the probe array by matrix-assisted laser desorption/ionization mass spectrometry (MALDI-MS). Micrometer-scale patterned amination of polymer surfaces is based on atmospheric-pressure dielectric barrier microdischarges (DBD) driven by medium-frequency voltages and has been achieved by the ignition of cold microdischarges in enclosed cavities after compressing the substrate with a suitably shaped "plasma stamp", based on PDMS (polydimethylsiloxane). Experiments have been carried out applying plasma stamps with cavity diameters of 1000  $\mu\text{m}$  and heights of 350  $\mu\text{m}$  in oxygen-free  $\text{N}_2 + 4\% \text{H}_2$  gas mixture. Two newly worked-out analytical methods, namely quantitative CD ATR-FTIR and CD SEM-EDX analyses, based on the selective gas-phase derivatization of primary amino groups with trifluoro-methyl-benz-aldehyde (TFBA) have been successfully utilized to evaluate the area densities of surface-bond  $\text{NH}_2$  groups introduced to the polymer surfaces. The results of CD SEM-EDX measurements have been shown to be in a reasonable agreement with average amino group densities determined by CD ATR-FTIR. Significant departures from spatial distribution uniformity of the functional groups within plasma modified areas are visible for the conducting substrate PP/C204. Up to 4 primary amines per  $\text{nm}^2$  have been measured to be attached area-selectively on the PP/C204 minidisks surfaces.

## REMOVAL OF PFCs FROM GAS STREAMS VIA PLASMA CATALYSIS

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With the characteristics of long lifetimes and high GWPs (global warming potentials), PFCs (perfluorocompounds) are regulated as one of the GHGs in Kyoto Protocol. Today, PFCs are widely used as etching or cleaning gases in semiconductor manufacturing and LCD manufacturing industries. The reduction of PFCs is an especially important issue in Taiwan, where the high-tech industries are highly developed.

Nonthermal plasma (NTP) technologies, such as dielectric barrier discharge (DBD), corona discharge, surface discharge and packed-bed plasma reactor, have been successfully applied to remove varieties of gaseous pollutants. However, the industrial application of nonthermal plasma technologies on gaseous pollutant removal is not popular because the energy efficiency and the byproducts<sub>j</sub><sup>-</sup> selectivities still need to be improved. To resolve these problems simultaneously, a novel technique termed as plasma catalysis has been developed accordingly. This novel technique, combining the advantages of high byproducts<sub>j</sub><sup>-</sup> selectivities from catalysis and the fast ignition/response from plasma technique, has been considered as the next generation nonthermal plasma technique for gaseous pollutant abatement.

In this study, two different plasma reactors, constructed by packing non-catalytic  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> or catalytic  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> pellets inside a DBD reactor, are used to remove C<sub>3</sub>F<sub>8</sub> from gas stream. The experimental results indicate that the combination of DBD and catalyst could effectively improve the energy efficiency and CO<sub>2</sub> selectivity for C<sub>3</sub>F<sub>8</sub> abatement. To get a better understanding of the better performance achieved with the combination of DBD and catalyst, five possible mechanisms, including the influence of packing pellets on plasma characteristics, thermal catalysis, adsorption of C<sub>3</sub>F<sub>8</sub> on  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>, O<sub>3</sub> decomposition by  $\gamma$ -Al<sub>2</sub>O<sub>3</sub> and the catalysis induced by the active species generated in plasma, are investigated by either experiment or simulation. The results indicate that the better CO<sub>2</sub> selectivity and higher energy efficiency are resulted from two different mechanisms. The former is caused by the active species generated from the O<sub>3</sub> decomposition by  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>. Moreover, the catalysis induced by the short-lived species generated in plasma is mainly responsible for the latter.



## **MICROPLASMAS AND PHYSICS 2010**

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## **THE RESEARCH GROUP “PHYSICS OF MICROPLASMAS” AT RUHR-UNIVERSITY BOCHUM**

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The presentation will give an overview over the Research Group “Physics of Microplasmas” which has been funded recently by the Deutsche Forschungsgemeinschaft DFG for a first period of three years. This coordinated research effort encompasses eight individual projects in the Departments of Physics and Astronomy and Electrical Engineering and Information Technology. The focus is on basic physics questions and on selected applied problems of microplasmas which are addressed experimentally as well as by theory and modeling.

## **REPORT ON THE MEXT CONSORTIUM ON MICROPLASMAS IN JAPAN FROM 2003 TO 2008**

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The research project on "Generation of micro-scale reactive plasmas and development of their new applications" (short title: Microplasma) has been organized as one of the programs of The Specific Research on Priority Areas for five years from August, 2003 to March, 2008 under the financial support by Grant-in-Aid for Scientific Research from Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) with the total budget of about 750 million yen. The project has been composed of three divisions categorized as (1) Generation of microplasmas, (2) Diagnostics and simulation of microplasmas, and (3) Applications of microplasmas. In each division, three core groups have been arranged based on the original plan and 5 to 10 groups have been added by the selection from public proposals. For the administration of the project, a steering committee has been operated by the project leader, the heads of three divisions, and a secretary with four advisory members. Practically, the project started with 9 core groups in the first year and executed the addition of 17 selected groups in the second year and the replacement and supplement of a few groups in the fourth year, ending up with 28 research groups in total. Within the period, a variety of new concepts have been created by combination of inherent properties of plasmas with specific characteristics of micro-scales. The other purposes of the project are the stimulation of collaborations between the research groups and the education of students and young researchers in the research field of microplasmas. In my talk I will briefly summarize the progresses and results of the project.

## **MICRO-PLASMA SCIENCE AND TECHNOLOGY IN THE UK: TOWARDS A NEW CONSORTIUM**

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Scientists and Engineers have become excited at the prospect of using micro-plasmas as miniature sources of charged, neutral and excited species for plasma materials processing and basic physics. These plasmas, which operate close to or at atmospheric pressure, have advantages over vacuum-based techniques in that the plasmas themselves can be scaled to a size approaching cellular dimensions, offering novel applications in medicine and biology, and are cheap, portable and very efficient in terms of power consumption. These plasmas also offer enormous opportunities for advancing technologies in a very wide range of other industrial sectors such as semiconductors, sensors and diagnostics, consumer electronics, spectroscopic analyses, environmental and energy. However, despite the advances in the technology there is still a lack of detailed fundamental understanding of the key processes in these plasmas on a microscopic level. To address this, a number of leading UK Physics and Engineering University Groups have initiated studies into a range of different micro-plasma geometries, including, plasma micro-jets, single cavity and multiple cavity arrays, micro-electrode devices and plasma micro-fluidic systems to name a few.

This paper outlines the current UK activity in fundamental and applied micro-plasma research and its efforts to form a critical mass in the topic to sustain this important activity into the future. In particular, it will discuss our attempts to form formal consortia and groupings, specifically in the areas of the physics of single cavity and multiple cavity-arrays and also in plasma micro-fluidic technology.

## PLASMA–WATER PROCESSES AND ELECTROHYDRODYNAMIC GAS-FLOW GENERATION USING MICRO PLASMAS

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DC/pulsed plasmas generated inside small gas-bubbles have been studied for water purification and nitric acid generation in water. The bubbles are formed by feeding a gas through a tiny hole of 0.2 mm in diameter at the center of a dielectric spacer. DC or pulsed voltage was applied between a high voltage electrode mounted just under the spacer and a grounded electrode immersed in the water. For water purifying experiments, repetitive pulsed voltage of 100 ns pulse width was applied to an oxygen bubble. Almost twenty pulsed plasmas were generated in one oxygen bubble and produced radicals decomposed acetic acid which was used as a persistent material. By replacing the gas to synthetic air ( $N_2/O_2=80/20$ ), nitric acid was efficiently generated within the water. The liquid phase products, such as  $NO_3^-$ ,  $NO_2^-$ ,  $H_2O_2$  were measured and evaluated by the zero dimensional simulation which included both gas and liquid phase reactions. The results showed that the products in water were generated through the oxidation of nitrogen in the gas phase by the reaction with OH or  $HO_2$  produced via plasma–water interaction. In both cases, plasma–water interaction seems to have the key role for enhancing the reactions in water.

Another application of sub-millimeter plasmas is the generation of electrohydrodynamic (EHD) gas-flow inside a narrow gap or capillary channel where a conventional mechanical fan is not applicable. A wire-rod (~0.1mm, 3 mm) electrode system was mounted on a surface of a dielectric material and the height of the channel, in which corona plasmas were generated, decreased below a few mm. A positive or negative corona plasma was generated in atmospheric air according to the polarity of a dc high voltage source, and generated ions collided with neutral molecules and transferred their momentum to the molecules, resulting in EHD gas flow. The flow velocity decreased with decreasing the height due to the pressure drop and the corona plasma instability. An electric charge control by the electrode configuration enabled gas flow generation below 1-mm height of the plasma channel.

## SELF CONTAINED MULTIPHASE MICROPLASMAS: BUBBLES IN HIGH PRESSURE GASES AND LIQUIDS

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The propagation of electric discharges in atmospheric pressure gases and liquids is typically through streamers. These streamers are transient and filamentary with diameters of tens to hundreds of microns. The streamers often spontaneously branch into sub-streamers which may in turn branch again. Positive streamers propagate by seeding electrons in front of the head of the streamer through photoionization. These electrons then avalanche in the large  $E/N$  of the space-charge enhanced streamer head, thereby extending and propagating the streamer. In liquids, the same basic process should occur, however the observed  $E/N$ , based on the density of the liquid, is typically too small to support the ionization process. Experimental observations suggest that streamers in liquids are in fact propagating through a gas phase with plasma first being produced in low density, randomly distributed bubbles of a few to tens of microns in size. For a given electric field, the  $E/N$  in the bubbles greatly exceeds that in the ambient liquid. Electron avalanche in the bubble produces locally large plasma densities and heating that extend the bubble and propagate the streamer. The plasma then becomes *multiphase*, gas and liquid. In this talk, results from a computational investigation of streamer propagation in a surrogate *multiphase* system will be discussed. Positive streamers propagating in high pressure ( $> 3$  atm) humid air with 'bubbles' (regions of low density) were modeled to provide insights to the liquid-bubble system. We found that photoionizing radiation from the primary streamer will seed avalanche in bubbles having large  $E/N$  which launches both positive and negative streamers from the bubbles. The proximity of the newly launched streamers to the primary (and other daughter streamers) then determine the path and pattern of branching of the discharge. The ability of the bubbles to launch streamers is, in part, determined by Paschen Law considerations.

## ATMOSPHERIC PRESSURE PLASMA GENERATION IN MICROBUBBLES FORMED IN SALINE SOLUTION

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Recently, application of microplasmas for biological and biomedical purposes has attracted much attention. Some types of atmospheric pressure plasma sources driven in saline solution for in-vivo medical treatments have been developed and put into practical uses [1,2]. In many cases of plasma in conductive liquid medium, a thin vapor layer and/or microbubbles form near the electrodes without gas injection. These bubbles are thought to form due to electrolysis and/or Joule heating and the plasmas generated there produce various excited species, such as OH, which are believed to be responsible for tissue removal in surgery. However, the detailed mechanisms of the plasma and the bubbles formation are not fully understood or controlled. In the present study, with the ultimate aim of development of highly-controlled plasma medical devices, we examined plasmas generated in bubbles formed in normal saline solution (0.85 wt% NaCl in H<sub>2</sub>O).

A titanium wire (126  $\mu\text{m}$  in diameter), covered by glass except at its tip, was used as the high-voltage electrode and inserted into saline solution. We employed an asymmetric square voltage waveform and controlled the magnitude ( $V_+$ ,  $V_-$ ) and duration ( $t_+$ ,  $t_-$ ) of negative and positive voltage phases, respectively. Another exposed titanium wire was placed in the same solution to act as ground return electrode.

We found that bubble behavior can be switched between a chaotic bubble cloud mode and stable single bubble mode by controlling the voltage waveform. In most cases of repetitive plasma generation at negative voltage phase, the bubbles formation and detachment occur iteratively and bubble cloud was formed. On the other hand, in some cases, we achieved repetitive plasma generation in a stable single bubble. When plasmas were generated only at positive voltage phase ( $V_{\text{peak},+} = 290 \text{ V}$ ,  $V_{\text{peak},-} = -80 \text{ V}$ ,  $t_+ = 5 \mu\text{s}$ ,  $t_- = 20 \mu\text{s}$ ), a single bubble (diameter of less than 1 mm) formed in contact with the high-voltage electrode surface without detaching. We also report plasma optical emission spectra corresponding to the different bubble and discharge modes.

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## NOVEL NANO-BIO MATERIAL FORMATION USING GAS-LIQUID INTERFACIAL MICROPLASMAS

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Utilizing a gas-liquid phase interfacial region of a hybrid system composed of ionic liquids and gas phase plasmas, could contribute to the effective creation and modification of nano-composite materials consisting of biomolecules, metal particles, nanocarbons and so on, which are dispersed in the ionic liquids. In order to realize the creation of the novel materials, the control of ion behavior in both the gas and liquid phases is desired. In this study, a microplasma source containing the ionic liquids is developed for clarifying the effects of the ionic liquids on the plasma generation and controlling the ion motion for the synthesis of the nano-bio materials in the micro reactive field between the plasma and the ionic liquids. A direct current (DC) discharge plasma is generated just above the ionic liquid by applying the DC voltage to an electrode immersed in the ionic liquid against a grounded electrode set in the gas phase region. The precise potential structure between these electrodes through the gas-liquid interfacial region is clarified, and the dynamics of the plasma ions are found to be controlled using the sheath electric field in the interfacial region. The control of the plasma ion irradiation flux and energy to the ionic liquid leads to the creation of various kinds of nanoparticles and the realization of particle shape and size control.



## ATMOSPHERIC DC GLOW MICRODISCHARGES USING ELECTROLYTE ELECTRODE AND AXIAL MINIATURE HELIUM FLOWS

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An atmospheric DC glow microdischarge using an electrolyte solution ( $\text{Na}_2\text{SO}_4$ ) as electrodes and axial miniature helium flow was generated stably in the wide range of gap separation from 0.1 to 20 mm in ambient air. It showed specific discharge characteristics, which were not observed in the metal electrode microdischarges. In the electrolyte cathode discharge of 0.3 % in concentration, with increasing the current from 5 mA, the intensity of negative glow became weak and disappeared at 20-30 mA. When the current was increased further, yellow light emission was observed in the negative glow region at 50 mA. Its intensity, which was originated from sodium atoms vaporized from the electrolyte surface, increased as the current increased. The sodium vapor appeared with a delay time from the start of the discharge, in which the emission of nitrogen molecular lines appeared and reached their peaks immediately. We tried to operate a dc power supply with a pulse-modulated mode to control the sodium atomic line emission. If the voltage was made zero before the vaporization occurred, the sodium emission was suppressed. The intensity of sodium emission decreased with decreasing the on-duty-ratio of dc modulation. The stable glow microdischarge using the electrolyte anode was also obtained. When the discharge current was 10 mA, the anode spot had a small circular shape. As the discharge current increased from 15 to 25 mA, the anode spot turned into a ring-like structure. Further increase of discharge current caused the anode structure to self-organize. When the distilled water anode was employed, the anode spot turned into a gear-shape structure at 35 mA. In contrast, when the electrolyte anode of 1% in concentration was employed, the ring-like structure became a double-ring-like one at 30 mA, and the outer ring was divided into a set of small spots at 35 mA. These self-organized structures could not be observed when the electrode separation was less than 5 mm. The dependence of the structure of self-organization on electrolyte concentration indicates that anion and cation in electrolyte play an important role for electrolyte anode discharges.

## POSTER SESSION I

1. "Modeling of Atmospheric Pressure Plasmas"  
H. W. Lee, Pohang University of Science and Technology
2. "Self-Consistent Simulation of Plasma and Gas Dynamics in Microplasmas"  
M. Jugroot, Royal Military College of Canada
3. "Modeling Cathode Boundary Layer Discharges"  
E. Munoz-Serrano, University of Cordoba
4. "Fluid Modeling of Microwave Micro-Plasmas at Atmospheric Pressure"  
J. Gregorio, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Laboratoire de Physique des Gaz et des Plasmas, Université Paris Sud
5. "Study of a Microwave Micro-Plasma Reactor at Atmospheric Pressure"  
J. Gregorio, J. Gregorio, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Laboratoire de Physique des Gaz et des Plasmas, Université Paris Sud
6. "Impedance of a Microwave Atmospheric Plasma During Ignition"  
S. Kühn, Gerdinand-Braun-Institut für Höchstfrequenztechnik
7. "Spatial and Temporal Resolved Surface Charge Measurement in a Dielectric Barrier Discharge"  
L. Stollenwerk, Institut für Plasmaforschung
8. "Investigation of Discharge Mechanisms in Microplasma Jet by Laser Spectroscopic Measurements"  
K. Urabe, Kyoto University
9. "Electric Field Measurements in Near-Atmospheric Pressure Nitrogen and Air Based on a Four-Wave Mixing Scheme"  
S. Mueller, Ruhr-University Bochum
10. "Coupling of Imaging and Emission Spectroscopy for Microplasma Studies"  
C. Lazzaroni, Ecole Polytechnique
11. "Absolute Atomic Oxygen Density Measurements Inside the Core and Effluent of a Micro-Scaled Atmospheric Pressure Plasma Jet"  
N. Knake, Ruhr-University Bochum
12. "Breakdown Voltage in Radio-Frequency Helium Microdischarges"  
M. Radmilovic-Radjenovic, Institute of Physics, Belgrade
13. "Theoretical Study of the Water Vapors Breakdown Voltage in Microgaps"  
M. Radmilovic-Radjenovic, Institute of Physics, Belgrade

14. "Power Deposition Scaling in an Atmospheric Pressure Capillary Dielectric Barrier Discharge"  
B. Sands, UES, Inc.
15. "Properties of Dielectric-Barrier-Free Atmospheric Pressure Micro Plasma Driven by Sub-Micro Second DC Pulse Voltage"  
H. -J. Lee, Pusan National University
16. "Self-Pulsing of a Micro Hollow Cathode Discharge"  
B. Du, Ruhr University Bochum
17. "Study of the Operational Properties of the Capillary Plasma Electrode (CPE) Discharge"  
J. Lopez, Saint Peter's College
18. "Time-Resolved Investigations of a Fast-Pulsed Dielectric Barrier Discharge"  
J. Lopez, Saint Peter's College
19. "A Comparison Study of Atmospheric Plasma Jets"  
Q. Nie, Loughborough University
20. "Kinetic Alfven Waves in the Presence of Ion Beam in Plasma Sheet Boundary Layer-Particle Aspect Analysis"  
J. Shrivastava, Invertis Institute of Engineering & Technology
21. "Direct Current Cathode Boundary Layer Xenon Discharges"  
W. Zhu, Saint Peter's College
22. "High Energy Density Electrons Controlled By Ultra-Intense Laser Coupled With A Micro-Pulse Power Discharged Fiber"  
A. Nishida, Osaka University

## MODELINGS OF ATMOSPHERIC PRESSURE PLASMAS

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Atmospheric pressure plasmas (APPs) are finding various possibilities for bio-medical applications such as coagulation, sterilization, skin care and even cancer diagnosis and treatment, thanks to their device portability and the non-thermal property [1]. Several simulation methods can be used for describing and obtaining the physical information of the APPs such as density profiles of several species, electron and ion energy distributions, potential profiles which cannot be obtained easily from experiments.

In this study, the comparison between particle-in-cell Monte-Carlo collision (PIC-MCC) and fluid simulations for helium APP sources was reported. The time-averaged densities, electric field and power consumption profiles obtained from two simulations showed the improved agreement at higher driving frequency [2, 3]. The kinetic information obtained from the PIC-MCC simulations indicated that the electron energy probability function (EEPF) was far from equilibrium, and three electron groups with three distinct temperatures were identified at the low driving frequency [4], and it became closer to a Maxwellian distribution as the driving frequency increased. Because the fluid simulations assume that the EEPF is a Maxwellian energy distribution, the physical information obtained from the fluid simulations were comparable with them obtained from the PIC-MCC simulations at higher driving frequency.

We also have developed the zero-dimensional global models of He/O<sub>2</sub>, Ar/O<sub>2</sub> and N<sub>2</sub>/O<sub>2</sub> to investigate the effects of the input power density and admixture of oxygen on the densities of several species and the electron temperature [5]. It was shown that the densities of electron increased as the input power increased and the admixture of oxygen decreased. The densities of electron, atomic oxygen and ozone of Ar/O<sub>2</sub> were higher than those of He/O<sub>2</sub>. The electron temperature of He/O<sub>2</sub> was higher than that of Ar/O<sub>2</sub>, and both of them decreased as the power density increases.

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## **SELF-CONSISTENT SIMULATION OF PLASMA AND GAS DYNAMICS IN MICROPLASMAS**

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There is a great interest in understanding plasmas in small spaces as the complexity of micro-technology systems increases. A self-consistent model of plasma and neutral gas dynamics is applied to atmospheric microplasmas in helium. Hydrodynamic transport equations of the self-consistent and time-dependant model are described with an emphasis on the different terms involved in the close coupling among charged species, neutral species and the electric field, including space charge. The microplasmas are studied from an initial cloud until the stages of charged particle over-amplification and breakdown, where transients are particularly important. Both metallic and dielectric electrodes are compared in terms of spatio-temporal evolution of the plasma and gas dynamics. Gas heating, neutral depletion initiation and electric field reversal are observed, highlighting the close interaction between neutral gas and charged species in governing the evolution of the microplasma.

## MODELING CATHODE BOUNDARY LAYER DISCHARGES

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A Cathode Boundary Layer Discharge or CBL (KH Schoenbach, M Moselhy, and W Shi, Plasma Sources Sci. Technol. 13 177, 2004) is an electrode/dielectric/electrode sandwich with a central hole pierced through the dielectric and one of the electrodes (the anode). This configuration differs from MicroHollow Cathode Discharges (MHCDs) in that the cathode surface area available to the discharge is limited by the annular dielectric. By limiting the surface area, the discharge operates in an abnormal glow mode with a positive current-voltage characteristic at higher current, and thus parallel operation of multiple CBLs is a possibility. Using a two-dimensional fluid model (JP Boeuf, et al Appl. Phys. Lett 86 071501, 2005), we have studied the electrical properties of CBLs in argon at pressures up to near atmospheric. In this communication, we show model results for the spatial profiles of the charged particle and metastable densities, the potential distribution and the gas temperature for a range of conditions. Calculated V-I characteristics for 100 and 400 torr for a 800 micron hole diameter will be presented and potential distributions from selected points will be used to illustrate the physics. One interesting result (anticipated in the work of SG Belostotskiy, et al, Plasma Sources Sci. Technol 17, 045018, 2008) is that the effect of gas heating is to limit the current that can be extracted from one CBLs. That is, there is a sharp increase in the slope of the V-I characteristic when gas temperature is taken into account. This effect is not observed when the discharge is able to expand on the outer surface of the cathode in the case of MHCDs, for example.

## FLUID MODELING OF MICROWAVE MICRO-PLASMAS AT ATMOSPHERIC PRESSURE

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This paper presents the numerical modeling of microwave (2.45 GHz) micro-plasmas at atmospheric pressure, in view of complementing its experimental characterization [1, 2]. The plasmas are sustained within the 50-200  $\mu\text{m}$  slit separating two metal blades (6-14 mm width), which constitute the end-gap of a microstrip-like transmission line. The reactor can produce high-density ( $\sim 10^{14} \text{cm}^{-3}$ ), low-power ( $< 10 \text{ W}$ ) plasmas in ambient air or in controlled environments (argon, helium, nitrogen, etc.), by using a continuous wave excitation.

The simulation tool is a one-dimensional (between the metal blades), stationary fluid-type code that solves the charged particle and the electron mean energy transport equations (for argon as a test gas), together with Poisson's equation for the space-charge electrostatic field and Maxwell's equations for the electromagnetic excitation field. The model uses a simple kinetic scheme for Ar, with only three energy levels: the ground state, an excited state representing the lumped 4s levels, and the ionization level. The model considers both direct and stepwise ionization processes and accounts for the presence of the molecular ion  $\text{Ar}_2^+$ , which contributes to the creation of the 4s excited level by dissociative recombination. Electron transport parameters and rate coefficients are obtained by adequate integration of collision cross-sections [3] over the electron energy distribution function, calculated by solving the two-term electron Boltzmann equation in the presence of inelastic and superelastic collisions with the 4s states. We adopt the local mean energy approximation [4, 5] in order to define a spatial profile for the electron parameters. The ions are assumed to be in thermal equilibrium with the neutral gas, for which we impose a constant temperature profile at  $\sim 600 \text{ K}$ .

The model is solved using a time relaxation algorithm that manages the different equations within almost independent calculation modules, which communicate after partial convergence only. This approach marks a real difference with respect to classical time-advancing algorithms, allowing the use of (faster) implicit features to solve this stationary problem.

Model results reveal the existence of combined kinetic-transport features, showing also that  $\text{Ar}_2^+$  is the dominant ion for the typical work conditions considered.

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## STUDY OF A MICROWAVE MICRO-PLASMA REACTOR AT ATMOSPHERIC PRESSURE

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In this paper, we study two microwave sources, which use a continuous 2.45 GHz excitation to produce stable microplasmas at atmospheric pressure. Both sources are based on a planar transmission line configuration, corresponding to linear resonators. Source 1 (S1) is similar to the one reported in [1]. Source 2 (S2) is a skilled evolution of S1 towards miniaturization, in order to enable system portability [2, 3].

In both sources, micro-plasmas are produced within the 50-200  $\mu\text{m}$  gap created between two metal electrodes (14 mm length in S1 and 6 mm length in S2) placed at the open end of a microstrip-like transmission line. At the other end of the line, a movable short circuit varies the line length, working as an impedance matching unit. In S1, the power is transmitted to a rectangular waveguide and then to a perpendicular coaxial line, whereas in S2 the power is directly transmitted to the coaxial line through a SMA transition. In S2, the coaxial line extends up to the top of the source, and acts as an additional impedance matching unit through its adjustable length.

The diagnostics of the gas rotational temperature,  $T_{\text{rot}}$ , and vibrational temperature,  $T_{\text{vib}}$ , are based on optical emission spectroscopy measurements. In air discharges, the temperatures are measured by comparing experimental and simulated spectra of the  $\text{N}_2$  second positive system (0-2 band system).  $T_{\text{rot}}$  is found between 900 and 1400 K, for coupled powers of 50-120 W in S1 and 30-50 W in S2.  $T_{\text{vib}}$  is of the order of 4500 K for S1 and of 5500 K for S2. In argon discharges,  $T_{\text{rot}}$  is measured by comparing experimental and simulated emission spectra of OH (A-X) (which is present as an impurity), and is found between 550 and 630 K for 7-14 W coupled powers. The excitation temperature  $T_{\text{exc}}$  is obtained from the Boltzmann plot of measured argon excited states, and is found between 0.45 eV and 0.55 eV for the same coupled powers.

Stark broadening measurements of the hydrogen beta line emission profile yield electron densities between  $8 \times 10^{13}$  and  $1.2 \times 10^{14} \text{ cm}^{-3}$ , for the work conditions considered.

The characterization of the reactors involves also numerical simulations, using a modeling tool in current development [4].

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## IMPEDANCE OF A MICROWAVE ATMOSPHERIC PLASMA DURING IGNITION

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We present time-resolved impedance measurements of the ignition process of low-power microwave plasmas. A 2.3 GHz coaxial quarter-wavelength resonator is used to excite the plasma. This plasma, in combination with a nitrogen gas flow, generates a plasma jet of several millimeters under atmospheric conditions. As well known, the resonator input impedances before and after ignition differ significantly. The subject of this paper is to present details on this transition process. This is very important for the development of matched microwave sources, for instance. The time-resolved impedance behavior is studied under different conditions, varying the microwave power level, the type of gas, and the flux. A dedicated measurement system was built to characterize the impedance behavior at microwave frequencies. Key component of the system is a vector network analyzer (VNA) with high time resolution. In combination with additional amplifiers to increase the microwave power level and bidirectional couplers to separate the incident and reflected waves, the VNA is able to handle power levels up to 30 watts. The measurement procedure consists of two steps. First, the resonator is measured at low power level in a frequency range around the resonance without plasma. This data is used to determine the resonance frequency and to extract an equivalent circuit of the resonator. The second step in our procedure is to drive the resonator with a short high-power microwave pulse at the previously determined resonance frequency thus igniting a plasma. The VNA records the change of the impedance with a bandwidth up to 30 MHz during the entire pulse duration. This includes the ignition instant and the following transition time the plasma needs to reach a steady state as well as the extinction process at the end of the pulse. The measurements were performed for various plasma excitation parameters. The time-resolved data provide interesting insights into plasma dynamics.

## **SPATIAL AND TEMPORAL RESOLVED SURFACE CHARGE MEASUREMENT IN A DIELECTRIC BARRIER DISCHARGE**

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In this work a dielectric barrier discharge system consisting of a narrow gas gap shorter than 1 mm with a wide lateral extension of several centimeters is investigated. With helium as working gas at a pressure of a few 100 hPa and a driving voltage of some 100 V at a frequency of 200 kHz a laterally structured discharge is observed. The system operates in the glow mode, i. e. there is a single breakdown per half-cycle of the driving voltage.

The observed discharges exhibit a large variety of different structures, most of them with dynamic changes on a timescale up to 10 ms. It is known that for the formation and stabilisation of the self-organised structures observed in the discharge the surface charges accumulating on the dielectrics play an important role. They represent an image of the structure in the last breakdown and act as a memory preserving the same structure in the subsequent breakdown.

In order to measure these surface charges, a BSO crystal is used as dielectric barrier. Via the Pockels effect the polarisation of an incident light beam becomes modulated and makes it possible to observe the surface charges during the running gas discharge experiment. In the presented measurements the spatial resolution is about 0.7 mm and the temporal resolution at least 1/100 s. Hence, it is possible to observe even dynamic structures in the discharge.

## INVESTIGATION OF DISCHARGE MECHANISMS IN MICROPLASMA JET BY LASER SPECTROSCOPIC MEASUREMENTS

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Various types of atmospheric pressure plasma jets (APPJs) have been developed and applied to material processes and novel bio-medical processes. We have examined an APPJ using a coaxial dielectric barrier discharge (DBD) configuration driven by an AC impulse voltage source of kHz order. A pair of copper sheets was wrapped around the capillary as electrodes and helium gas was fed into the glass capillary tube. It has been commonly observed by an ICCD camera that a bunched emission like a bullet is ejected from the capillary exit synchronously with the driving frequency in the positive phase, when the front electrode becomes positive. Its propagating velocity is several tens of km/s, which is higher than the gas flow velocity by three orders of magnitude.

In this report, we present our measurements on the spatiotemporal behaviors of the density distributions of excited species in the APPJ investigated by laser spectroscopic methods. We used a laser induced fluorescence (LIF) method for  $N_2^+$  ions, a laser absorption spectroscopy (LAS) method for helium metastable atoms, and also a time-resolved optical emission spectroscopy (OES) method for radiative species.

From the experimental results of LIF measurements, the rotational temperature of nitrogen ions was near room temperature, and the drift velocity of  $N_2^+$  ions was much lower than the apparent bullet speed. These results verify that the discharge mechanism of the plume is due to the propagation of ionization wave like that of positive corona streamer. At the exit of the nozzle, the radial density distribution of excited species inside the streamer had a ring shape with a hollow in the center. It is suggested that the streamer is triggered by the localized breakdown with the electric field by the surface accumulated charge inside the capillary.

In addition, we focus on the discharge mode change of the DBD when a grounded substrate is placed in front of the jet, since it is important in the application of this APPJ to material processes. In contrast to the case without the substrate, we observed higher densities of excited species in the negative phase of the applied voltage, and the radial density distributions in this phase were more uniform than in the positive phase. This difference is brought about by the grounded electrode placed in a finite distance from which a streamer is provided in the negative corona discharge phase. We will show more details of the experimental results in the presentation.

## **ELECTRIC FIELD MEASUREMENTS IN NEAR-ATMOSPHERIC PRESSURE NITROGEN AND AIR BASED ON A FOUR-WAVE MIXING SCHEME**

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An important parameter for understanding physics of discharges is the electric field strength. Knowledge of the spatial and temporal distribution of the field strength can provide information about the distribution of charged particles, current density and dissipated power.

Various non-invasive optical methods based on stark-effect have been developed for low pressure environment (1-100 Pa). Due to quenching effects, however, these techniques are not suitable for experiments in a high-pressure region, where many novel plasma applications have been reported. In this work, we therefore employ a different field measurement technique, i.e. a field-induced coherent Raman scattering (CRS) method for estimating the electric field strength locally in nitrogen and air environments at higher pressures.

The basic principle follows a four-wave mixing scheme. In this scheme, the third wave with frequency zero is represented by the electric field. In the mixing process coherent radiation at an infrared wavelength (at  $\sim 4 \mu\text{m}$ ) is generated. The intensity of generated infrared radiation ( $I_{\text{IR}}$ ) scales with the square of electric field the square of nonlinear susceptibility, and the incident laser intensity. By measuring the signal intensity, this relation therefore yields a simple method for estimating the field strength.

The measurements are performed with a frequency doubled Nd:YAG-Laser at 532 nm and a dye laser tuned to 607 nm. Field-dependent radiation  $I_{\text{IR}}$  (at  $\sim 4 \mu\text{m}$ ) is detected by an InSb-detector, field-independent radiation  $I_{\text{CRS}}$  (at  $\sim 473 \text{ nm}$ ) by a photo-diode. Measurement is conducted between two stainless steel electrodes with a gap length of 3.15 mm and applied field up to 1 kV/mm. The working medium is pure nitrogen at 1-2.5 atm pressure and an open air environment.

On the poster, results of the experiments are presented.

## COUPLING OF IMAGING AND EMISSION SPECTROSCOPY FOR MICROPLASMAS STUDIES

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Microplasmas refer to various types of discharges. Our work is focused on microhollow cathode discharges (MHCDs). One of the advantages of the MHCDs is their possibility to be generated at high pressure with a very low applied voltage or injected power.

A microplasma is generated in the microhole of a molybdenum-alumina-molybdenum sandwich at medium pressure. The gas pressure range from 30 to 300 Torr and the hole diameter from 100 to 400  $\mu\text{m}$ .

In pure Argon, the aim of our experiment is to study the radial dependence of the mechanism of atoms excitation and of the electronic density inside the microhollow cathode discharge. Imaging of the emission from the microplasma is performed with a spatial resolution of 2  $\mu\text{m}$ . The radial distribution of the emission intensities of an Ar atomic line and an Ar<sup>+</sup> ionic line are used for the excitation study. Ar and Ar<sup>+</sup> lines are excited in the cathode sheath edge by beam electrons accelerated within the sheath. These two excitations show the decay of the energy of electrons in negative glow. The Ar line presents also production of excited atoms by recombination of argon ions with electrons at the center of the microhole. The electron density is estimate from the Stark broadening of the H $\beta$ -line. In order to evaluate the contribution of the static electric field on the Stark broadening, we use a simple model based on a one-dimensional description of the plasma. It gives the radial evolution of the electron density which is compared to experimental results, and also the radial evolution of the electrons temperature. The first results of the simulation are in good agreement with the radial evolution of the electron density found experimentally.

## ABSOLUTE ATOMIC OXYGEN DENSITY MEASUREMENTS INSIDE THE CORE AND EFFLUENT OF A MICRO SCALED ATMOSPHERIC PRESSURE PLASMA JET

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The coplanar micro atmospheric pressure plasma jet ( $\mu$ -APPJ) is a capacitively coupled radio frequency discharge (13.56 MHz, ~15 W rf-power) designed for optimized optical diagnostic access. It is operated in a homogeneous glow mode with a noble gas flow containing a small admixture of molecular oxygen. This device matches typical dimensions of other microplasma jets. The coplanar geometry simplifies modelling and an electrode width of 1 mm provide a discharge profile of 1 mm<sup>2</sup> for localized surface treatment at a low gas consumption.

We report on spatially resolved atomic oxygen density measurements from the discharge core to the effluent of the  $\mu$ -APPJ [1, 2], being in good agreement with recent simulation data [3]. Ground state atomic oxygen densities in the effluent in the order  $10^{14}\text{cm}^{-3}$  are measured by xenon calibrated two-photon absorption laser-induced fluorescence spectroscopy (TALIF) providing space resolved density maps. The influence of gas mixture and rf sender power on the atomic oxygen densities in the effluent is studied. In the discharge core ground state atomic oxygen densities of several  $10^{16}\text{cm}^{-3}$  are measured. Special emphasis is set on the decay behaviour in the transition region from core plasma to effluent and it's dependence on the operational parameters. While e.g. the gas temperature in the effluent can be examined by thermocouples, for the plasma core optical methods are used.

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## BREAKDOWN VOLTAGE IN RADIO-FREQUENCY HELIUM MICRODISCHARGES

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Mechanism responsible for a gas breakdown has been studied from the early days of gaseous electronics. Recent studies of the breakdown phenomena, especially breakdown in small gaps, emerged in consideration of its practical applications as well as a fundamental importance. In this paper, the Kihara equation has been applied in order to determine dependence of the rf breakdown voltage on the pressure times the characteristic distance between two electrodes and the frequency in helium rf microdischarges. Numerical solutions of the Kihara equation and their good agreement with the available experimental data confirm that the Kihara equation, with modified molecular constants, describes the breakdown process well even for gaps of the order of a few millimeters.

## THEORETICAL STUDY OF THE WATER VAPORS BREAKDOWN VOLTAGE IN MICROGAPS

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Micro discharges can be regarded as a new class of plasmas that allow formation of non-equilibrium plasmas at atmospheric pressures. Since microdischarges operate under conditions where boundary effects dominate dictates the importance of establishing scaling laws in case of microns separations between the electrodes. In this paper, the failure of the breakdown voltage from the Pachen's law in microgaps is theoretically studied. In the standard DC breakdown criteria the enhancement of the secondary emission coefficient has been included. The obtained expression is than applied to determine the operational conditions in water vapors microdischarges. The obtained results apart from their theoretical relevance, have practical implications for the construction of compact pulse power generators for bioelectric applications.



## POWER DEPOSITION SCALING IN AN ATMOSPHERIC PRESSURE CAPILLARY DIELECTRIC BARRIER DISCHARGE

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A capillary dielectric barrier discharge (CDBD) driven by submicrosecond unipolar pulsed excitation has been used as a source for generating a stable, nonequilibrium, cold atmospheric pressure plasma channel in air for the efficient generation of reactive species. In open air, this source is similar in appearance to atmospheric pressure plasma jet (APPJ) devices but differs in that the plasma channel is supported by a streamer initiated self-sustained glow-like discharge rather than the flow-driven effluent from a separate discharge within the capillary. Consequently, this source can be sustained at lower feed-gas flow rates. The narrow plasma channel is confined to the capillary axis owing to a spatiotemporally reproducible streamer discharge that is guided by both the rare gas flow and a focusing of the electric field along the capillary axis. When used with a cathodic ground plane downstream, the streamer initiated plasma channel can carry high current from 100 mA to over 1 A. We used a 12 kV positive voltage pulse with a 20 ns rise time and 150 ns on time that was repeated at a 1 kHz rate for this experiment. The flow gas was a 5% Ar/He Penning mixture flowed at a rate of 2 standard l/m. We have characterized the power deposition scaling from electrical measurements and spatiotemporally-resolved optical emission spectroscopy in combination with gated-ICCD imaging as a function of the gap length and cathode material. Besides the plasma emission from electronically excited Ar and He, the gradual entrainment of air in the rare gas core allows for measurement of relative optical emission intensities from N<sub>2</sub> and N<sub>2</sub><sup>+</sup> at 337 and 391 nm, respectively. It is shown that the integrity of the rare gas core has important consequence for power deposition in the gap. As the gap size is reduced, the current first slowly increases then is followed by a sharp increase in slope. This knee of the current increase is shown to correspond to a transition between an air dominated and Ar/He gas dominated cathode layer. The importance of the cathode layer in this source is demonstrated by a significant enhancement in the emission intensities from the observed plasma species. The composition of the cathode also is shown to significantly impact the stability of the discharge. This is potentially important for applications in material processing and separates this discharge source from other flow-driven APPJ sources.

## PROPERTIES OF DIELECTRIC-BARRIER-FREE ATMOSPHERIC PRESSURE MICRO PLASMA DRIVEN BY SUB-MICRO SECOND DC PULSE VOLTAGE

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Atmospheric pressure micro plasma driven by DC pulse has been developed. It has very simple structure consist of dielectric-free metal electrodes without external current limiting resistor. By limiting the voltage pulse width shorter than 500 nsec, stable glow mode plasma could be sustained without arc runaway. Properties of the developed plasma system have been investigated as a function of helium flow rate using spatio-temporally resolved optical emission spectroscopy. Rotational temperature of N<sub>2</sub><sup>+</sup>, for the representative experimental condition, was measured about 850 K at the current peak, 600 ~ 350 K during the afterglow. Discharge voltage and time lag increase and discharge current decreases with the flow rate of helium feed gas. Optical emission from N<sub>2</sub> decreases with helium flow and emission of N<sub>2</sub><sup>+</sup> shows its maximum at the intermediate helium flow rate. It is shown that the change of partial pressure ratio between He and N<sub>2</sub> with helium flow rate is one of the most important factors affect the discharge properties. Emission from excited oxygen atom O increases with flow rate in spite of reduction of discharge current. Temporally resolved emission spectra have shown that the enhancement of emission from oxygen for higher He flow condition mainly comes during the afterglow. This suggest that dissociative excitation of O<sub>2</sub> by He metastables is very important process for the efficient generation of oxygen radicals in flowing helium atmospheric plasma system.

## SELF-PULSING OF A MICRO HOLLOW CATHODE DISCHARGE

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Micro hollow cathode discharges (MHCD) consist of two electrodes separated by a thin dielectric (100 mm). The discharge develops in a hole penetrating all three foils (200 mm diameter). When powered by a DC voltage of several 100 V, the discharge shows self-pulsing operation. The pulse frequency can range from several kHz up to about 1 MHz and the pulse width can be as short as several 10 ns. In these pulses peak currents as high as 100 mA are measured. Assuming a homogeneous distribution of the current across the hole, this is equivalent to peak current densities of the order of  $300 \text{ A/cm}^2$ . However, optical emission measurements with a gated ICCD camera equipped with a microscope lens show that the discharge pulses constrict within the hole. This makes current densities in the  $\text{kA/cm}^2$  range more likely. The self-pulsing and the discharge ignition is investigated in argon at pressures ranging from several 1000 Pa to atmospheric pressures and powered by DC voltages ranging from several 100 V to 2000 V. The pulse frequency is related to the capacitance of the discharge setup. Due to the smallness of all components stray capacitances are actually quite important. The circuit is critically analyzed and consequences for interpretation of the measured current waveforms are discussed. The voltage-current characteristic shows a transition from abnormal mode to spark mode as in a DC glow discharge. There are indications that the heating of the gas in the discharge gap by the high peak current is crucial for the stability of the pulsing mode operation.

## **STUDY OF THE OPERATIONAL PROPERTIES OF THE CAPILLARY PLASMA ELECTRODE (CPE) DISCHARGE**

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Various approaches have been pursued to create stable atmospheric pressure discharges by extending the lifetime of the diffuse phase of the discharge to hundreds of microseconds. Extensive research has found that the stability of the diffuse mode is dependant on the frequency (in the kilohertz range), gas type, power of the excitation, and geometrical confinement. Some of the most promising results have come from this later approach based on the recognition that arc formation in high-pressure plasmas can be avoided and stable high-pressure plasmas can be generated and maintained when the plasmas are spatially constricted to dimensions of tens to hundreds of microns. The Capillary Plasma Electrode (CPE) discharge introduced by Kunhardt and Becker is able to produce stable atmospheric pressure nonequilibrium plasmas. The CPE discharge is essentially a barrier-electrode discharge with perforated dielectrics. The discharge from this configuration, aside from exhibiting a diffuse mode of operation, also exhibits a distinct mode namely the capillary jet. As the frequency of the source is increased above a few kilohertz, one first observes the diffuse mode, but when a certain frequency is reached the capillaries turn on and bright plasma jets are observed to emerge from the capillaries. The distinction between the diffuse and capillary modes is dramatic. The capillary jets seem to overlap so that the discharge appears uniform when the electrode contains an array of capillaries. This current work explores these modes of operation by characterizing the electrical and optical emission properties of this discharge by correlating a multi-capillary discharge and a single capillary discharge reactor.

## TIME-RESOLVED INVESTIGATIONS OF A FAST-PULSED DIELECTRIC BARRIER DISCHARGE

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Dielectric Barrier Discharges (DBDs) produce highly non-equilibrium plasmas that allow for the effective generation of ions, excited species, and radicals from energetic electron-driven processes. In an effort to improve the production of the excited species, radicals, and UV radiation, which are all strongly influenced by the reduced electric field, it is more effective to use a pulsed high voltage of very short duration, particularly if the aim is to keep the gas temperature low. In order to better understand the involved physical phenomenon, time-resolved electrical measurements in conjunction with the established methods of time-resolved optical emission spectroscopy (TR-OES) and time-resolved imaging were utilized to characterize the fast-pulsed discharge.

## A COMPARISON STUDY OF ATMOSPHERIC PLASMA JETS

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Atmospheric pressure plasma jets are well-suited for treating uneven and essentially three-dimensional objects. Although different jet configurations have been put forward, their relative merits remain unclear. In this work, five different jets are studied based on three different configurations but all excited at 30 kHz. The first consists of a ring electrode wrapped around a dielectric tube, while the second employs an injection needle placed inside a hollow dielectric tube. The third is a hybrid of the first two configurations. Further variations are added to the three different configurations in terms of electrode connection. For all five plasma jets, the free-burning length of the plasma plume has a similar maximum value of approximately 2 cm with the applied voltage up to 10 kV and the helium flow rate up to 5 liters per minutes. However the spatial distribution of the optical emission is different along the length of different plasma plumes. We also consider the optical emission intensity of excited atomic oxygen lines at 777 nm and 845 nm at the contact point of the plasma jet on the surface of a downstream metal sample (1cm away from the jet nozzle). Our results suggest that low breakdown voltage and high atomic oxygen production are achieved simultaneously when both the injection needle and the ring electrode are connected to the high-voltage terminal. Polypropylene film treated by this plasma jet clearly shows oxidation effect after a short plasma exposure. This understanding provides a useful knowledge base for future parallelisation of single jets to form large-scale jet array sources.

## KINETIC ALFVEN WAVES IN THE PRESENCE OF ION BEAM IN PLASMA SHEET BOUNDARY LAYER - PARTICLE ASPECT ANALYSIS

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**Abstract** – This work studies the effect of upward (tailward) directed ion of electron thermal energy density to magnetic field energy  $\beta$  beam, the ratio density and the ratio of ion to electron thermal temperature ( $T_i/T_e$ ) on kinetic Alfvén wave in plasma sheet boundary layer (PSBL). The particle aspect approach is adopted to investigate the trajectories of charged particles in the electromagnetic field of kinetic Alfvén wave. Expressions are found for the dispersion relation, damping-rate and associated currents in the presence of ion beam in homogenous plasma. Kinetic effects of electrons and ions are included to study kinetic Alfvén wave because both are important in the transition region. The plasma parameters appropriate to plasma sheet boundary of  $\beta$  layer are used. It is found that upward directed ion beam, the ratio electron thermal energy density to magnetic field energy density and the ratio of ion to electron thermal temperature ( $T_i/T_e$ ) affect the dispersion relation, damping-rate and associated currents in both cases (warm and cold electron limit). The treatment of kinetic Alfvén wave in the presence of ion beam is based on the assumption that the plasma consists of resonant and non-resonant particles. The resonant particles participate in an energy exchange process, whereas the non-resonant particles support the oscillatory motion of the wave. **Key- words:** Magnetospheric physics (Plasma waves and instabilities; Ion beam) – Space plasma physics (Wave-particle interactions)

## **DIRECT CURRENT CATHODE BOUNDARY LAYER XENON DISCHARGES**

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Direct current Cathode Boundary Layer (CBL) discharges were generated in xenon between a blind cathode and a perforated anode (diameter: 750 micrometer), separated by a distance of 100 - 250 micrometer. Molybdenum, copper, aluminum, silicon (p-type) were used as cathode materials. End-on photographs in the visible range and at the wavelength of excimer emission for xenon (172 nm), together with voltage-current characteristics were recorded at pressures ranging from 75 to 400 Torr. Upon ignition, when current was reduced, a clear transition from homogeneous plasma to self-organized patterns was observed for certain electrode materials. Excimer emission intensity due to different cathode material and cathode material modification by CBL discharges will be briefly assessed.



## HIGH ENERGY DENSITY ELECTRONS CONTROLLED BY ULTRA-INTENSE LASER COUPLED WITH A MICRO-PULSE POWER DISCHARGED FIBER

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High power laser technologies are opening a variety of attractive fields of applications based on high energy density physics, e.g. ion and electron acceleration, laboratory astrophysics, x-ray lasers and fast ignition of laser fusion. These applications had been limited in the control of the high power laser technology and their optics. However, now we have a novel tool to control the intense light and high density of energetic particles, which is a plasma photonic device [1] consisted of transient high energy density plasmas. One of the functions of the devices is control of high density MeV electrons generated by ultra-intense light taking account of return current in high density plasmas. High temperature plasmas are well conductors to propagate the return current and the energetic electrons follow the conductors. Energy PW lasers can create high density energetic electrons with a large amount of the total energy, resulting in guide of the energetic electrons with self generated high density and high temperature plasmas. On the other hand, table top lasers can generate energetic electrons but no high temperature conditions to be a well conductor.

Here, we have proposed introducing a micro pulse power technology in high power laser plasma experiments to boost up the return current in low temperature plasmas, resulting in efficiently guiding of energetic electrons. High current pulse power generators with a rise time of nsec, which is switched by a pulse laser trigger system, are developed as a role of booster of the return current in the cone-wire device to guide the energetic electrons [1]. This high current micro pulse power is also useful in generation of a strong magnetic field in a small area such as laser plasma experiments. We have a plan to use this hybrid system to generate strong magnetic field and its applications in laboratory astrophysics, material science and novel radiation source development.

### References

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## POSTER SESSION II

1. "Cold Atmospheric Plasma Jets Arranged in a Honeycomb Array"  
Z. Cao, Loughborough University
2. "Independently Addressable, Parabolic Cross-Sectional Al/Al<sub>2</sub>O<sub>3</sub> Microcavity Devices: Improved Luminous and Luminance Efficacy by Controlling Cavity Geometries"  
K. S. Kim, University of Illinois
3. "Hybrid Microcavity and Microchannel Plasma Arrays Fabricated in Aluminum Foil: Large Scale Array Fabrication and Discharge Characteristics"  
K. S. Kim, University of Illinois
4. "Transparent, Flexible Microplasma Arrays Fabricated by a Replica Molding Process"  
J. Ma, University of Illinois
5. "Formation of Microplasma in Small Capillaries"  
S. Panowitz, University of Stuttgart
6. "Glass Microchannel and Microcavity Arrays: Dependence of Plasma Properties on Device Structure and Electrode Geometry"  
S. H. Sung, University of Illinois
7. "Silicon Microplasma Arrays: Investigating Microplasma Operating Characteristics and Collective Phenomena"  
Paul Tchertchian, University of Illinois
8. "One Chip, Al/Al<sub>2</sub>O<sub>3</sub> Mesh Microplasma Devices: Formation of Micro-Tip Arrays and Discharge Characteristics"  
Je Kwon Yoon, University of Illinois
9. "Degradation Study of Lead Zirconate Titanate for Use in a Ferroelectric Plasma Source"  
B. C. Masters, University of Illinois
10. "Plasma Diagnostics of Underwater Electrical Diaphragm Discharges for Textiles Treatment"  
A. Brablec, Masaryk University
11. "Recent Progress in Applications of Coplanar Surface Barrier Discharges for Low-Cost High-Speed Material Processing"  
M. Cernak, Comenius University
12. "Localized Surface Treatment Using a Microwave Generated Surface Wave Microplasma"  
J. J. Narendra, Michigan State University
13. "Reduction of Gaseous Dimethyl Sulfide (DMS) Using Coaxial Dielectric-Barrier Discharge at Atmospheric Pressure"  
H. – H. Chen, National Cheng Kung University
14. "The Fundamentals of Microplasma Source for the Analysis of Gases by the Method of Collision Electron Spectroscopy (CES)"  
A. Kudryavtsev, St. Petersburg State University

15. "Time Resolved Spectroscopic Measurement of High-Power Pulsed Microplasma for Elemental Analysis"  
Y. Nagata, Tokyo Institute of Technology
16. "Deposition of Diamond-Like-Carbon Films using Transient Glow Microdischarges Powered by Fast Pulse-Train Voltages at Atmospheric Pressure"  
S. Ibuka, Tokyo Institute of Technology
17. "Characterization of Arc Extinction using Pulsed Micro-Arc Discharge with CO<sub>2</sub> Gas Blasting"  
M. Kanemaru, Tokyo Institute of Technology
18. "New Sustain Waveform for Improving the Luminous Efficacy in a Wide Gap Plasma Display"  
J. -H. Seo, University of Incheon
19. "Non-Thermal Plasma Devices at Atmospheric Pressure for Biomedical Applications"  
Y. S. Seo, Pohang University of Science and Technology
20. "The Effect of Atmospheric Pressure Micro Plasma on the Degradation of Integrins and Focal Adhesion Kinase in G361 Melanoma Cells"  
H. J. Lee, Pusan National University
21. "Influence of Plasma Chemistry on the Plasma Needle-Biomaterial Interaction"  
Y. Sakiyama, University of California at Berkeley
22. "Microplasmas At The Tip Of Al/Al<sub>2</sub>O<sub>3</sub> Microscopic Electrodes In Water Or Saline Solutions"  
Y. Sakiyama, University of California at Berkeley
23. "Microplasma Production of Singlet Oxygen at Atmospheric Pressure for DNA Oxidation"  
J. Santos Sousa, LPGP, CNRS-UPS and IPFN IST
24. "Inactivation of Bacteria in Aqueous Environment by Atmospheric Pressure Non-Thermal Plasma"  
P. Sun, Peking University

## **COLD ATMOSPHERIC PLASMA JETS ARRANGED IN A HONEYCOMB ARRAY**

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Cold plasma jets generated at atmospheric pressure represent a rapidly developing technology of great application promises. Less influenced by the downstream sample, they are well suited for material processing of uneven surfaces. In this contribution, we present a study of a group of 19 cold atmospheric helium plasma jets densely arranged in a honeycomb array and energised by a sinusoidal excitation voltage at 10-30 kHz. The jet matrix can produce a uniform plasma over a surface area of 2.6 cm<sup>2</sup>. For each element component, the barrier-jet discharge plasma is initiated between a powered needle injection electrode with a helium flow and a grounded ring electrode. The structure of the electrodes is designed to reduce the breakdown and sustaining voltages, and increase the density of reactive chemical species. As the discharge volume is scaled up in size, it becomes more difficult to maintain the plasma stability of the plasma jet array. We employ a ballast network to enhance the uniformity and stability of the jet array. Thus, all jets can be ignited together simultaneously with similar individual optical emission intensities and discharge currents.

**INDEPENDENTLY ADDRESSABLE, PARABOLIC CROSS-SECTIONAL AL/AL<sub>2</sub>O<sub>3</sub> MICROCAVITY DEVICES: IMPROVED LUMINANCE AND LUMINANCE EFFICACY BY CONTROLLING CAVITY GEOMETRIES**

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Microcavity plasma arrays having parabolic cross-sections as small as 80  $\mu\text{m}$  have been fabricated by electrochemical processes. An addressable electrode configuration was formed by self-patterning of ring Al electrodes in anodic aluminum oxide. Complete anodization of the aluminum layers results in self-patterned, azimuthally symmetric electrodes surrounding each microcavity and a dramatic decrease in array capacitance without sacrificing the electrical conductivity of the electrodes and interconnects. Microcavity geometries are controlled precisely by the electrochemical process sequence. By specifying the cross-sectional geometry of the cavities and the electric field strength inside the device, we have obtained improved luminance and efficacy in rare gas mixtures with Xe content up to 50 %. Emphasis has been placed on controlling all device dimensions to within 2% while scaling the size of the array. Arrays as large as 20000 devices in an active area of 100 cm<sup>2</sup> have been fabricated and tested. Ne/Xe gas mixtures have been investigated at a total pressure ranging from 300 Torr to one atmosphere, and both pulsed and AC excitation waveforms. With a green phosphor coating in the microcavities, a luminance value of 1900 cd/m<sup>2</sup> has been achieved in Ne/30% Xe mixtures at 700 Torr.

## **HYBRID MICROCAVITY AND MICROCHANNEL PLASMA ARRAYS FABRICATED IN ALUMINUM FOIL: LARGE SCALE ARRAY FABRICATION AND DISCHARGE CHARACTERISTICS**

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Hybrid microcavity and microchannel plasma devices exhibiting enhanced reliability and lifetime relative to previous microcavity devices have been fabricated in aluminum foil. We have successfully fabricated arrays of microchannel devices in which electrodes and electrical connections are fabricated in a single sheet of aluminum foil by electrochemical processes. Aluminum driving electrodes and interconnects are fabricated and simultaneously encapsulated by  $\text{Al}_2\text{O}_3$  which acts as a dielectric barrier layer for discharge excitation. By combining microchannel devices with microcavities, addressable, self-assembled hybrid structure microplasma arrays have been fabricated with active areas as large as  $100 \text{ cm}^2$ . A notable aspect of this structure is that it provides for several distinct discharge modes and a geometry that allows for the optimal extraction of emission. The devices produce uniform glow discharges inside the microcavities without noticeable cross-talk over a wide range in gas mixtures and gas pressures. The operational parameters and addressability of these arrays will be discussed in detail.

## TRANSPARENT, FLEXIBLE MICROPLASMA ARRAYS FABRICATED BY A REPLICA MOLDING PROCESS

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The fabrication of flexible, and optically transparent, arrays of microplasma devices having microcavities fabricated by a polymer-based, replica molding process is reported. This process enables arrays of microcavity plasma devices or microchannels with feature sizes as small as  $\sim 10\text{ }\mu\text{m}$  to be produced inexpensively and precisely over surface areas of at least tens of  $\text{cm}^2$ . Hermetically sealed or restricted gas flow microplasma arrays with various microcavity geometries are successfully demonstrated for applications such as transparent displays, micro-reactors, and micro-fluidic cell detectors. As one example, tests of  $10 \times 10$  arrays of  $400\text{ }\mu\text{m}$  dia. devices with  $125\text{ }\mu\text{m}$  wide gas flow channels have been conducted in rare gas and Ar/CS<sub>2</sub> flows and excitation of  $\sim 505\text{ }\mu\text{m}$  the array with a sinusoidal voltage waveform. Visible chemiluminescence ( $\sim 400\text{ nm}$ ) resulting from the  $\tilde{A}^1\Sigma^+ \rightarrow \tilde{X}^1\Sigma^+$  transition of CS<sub>2</sub><sup>+</sup> and the deposition of a (C – S)<sub>n</sub> microstructured polymer have been observed in Ar/CS<sub>2</sub> flow experiments. The electrical and optical properties of these plastic-based microplasma arrays will be discussed.

## FORMATION OF MICROPLASMAS IN SMALL CAPILLARIES

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The surface modification of small and narrow volumes, like capillaries, for chemical and medical applications using plasma glow discharges is still a challenge. By plasma generation inside these small volumes, it is possible to coat or to clean inner surfaces or to functionalize them with different chemical groups like amino or carboxylic ones. Realizing a glow discharge in these volumes crucially depends on the geometry and the gas pressure in the experimental setup. We investigated plasma formation in capillaries made of glass or different polymers with diameters between 250  $\mu\text{m}$  and 5 mm in a pressure range of several mbar. For treatments of temperature sensitive polymers, it is important to keep the gas temperature below the melting temperature of the polymer. To characterize the plasma, it was analyzed by optical emission spectroscopy (OES) and temperature measurements. The optical emission properties are correlated with the temperature on the outer side of the quartz capillary. There are different methods to determine electron temperature, electron density or gas temperature from optical emission. From line intensities of molecular nitrogen it is possible to determine the rotational temperature of  $\text{N}_2^+$ , which is assumed to be the same as the neutral gas temperature. By investigating the interaction of pressure, frequency, and power, it was found that for low plasma-gas temperatures, it is necessary to work in the minimum of the Paschen-curve. Furthermore, the kHz-region is a good choice.



## **GLASS MICROCHANNEL AND MICROCAVITY ARRAYS: DEPENDENCE OF PLASMA PROPERTIES ON DEVICE STRUCTURE AND ELECTRODE GEOMETRY**

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Arrays of glass microcavities and channels with cross-sectional diameters less than 50  $\mu\text{m}$  and controllable geometries have been successfully fabricated by micropowder blasting techniques. Through a replica molding process, micro-patterned masks were formed precisely on the glass before the micropowder blasting process with which microchannels as small as 20  $\mu\text{m}$  on width can be generated. Arrays having as many as 1000 microcavities were fabricated on 400  $\mu\text{m}$  thick soda lime glass and the total thickness of a completed, hermetically sealed device is less than 1 mm. Stable, uniform glow discharges are observed for gas pressures up to one atmosphere. The glass microchannel plasma devices with either symmetric or asymmetric structures having dimensions of 30-200  $\mu\text{m}$  have been realized, and the spatially-resolved emission from these devices has been investigated for various gas mixtures. The dependence of device performance on the cross-sectional geometry of these fully-isolated microcavities will be presented.

## **SILICON MICROPLASMA ARRAYS: INVESTIGATING MICROPLASMA OPERATING CHARACTERISTICS AND COLLECTIVE PHENOMENA**

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A variety of silicon microcavity plasma arrays, both addressable and non-addressable, have been fabricated in sizes up to  $500 \times 500$  devices. The operating characteristics of these arrays have been examined primarily through detailed measurement of emission spectra in the ultraviolet, visible, and infrared. Several arrays were used to measure the effects of driving frequency and voltage as well as to record spectra. During these measurements, two distinct modes of microplasma operation and phenomena associated with the coupling between adjacent microplasmas were observed. Detailed cross talk measurements were also made for single pixels in a larger array and these results as well as representative spectra will be presented.

## ONE CHIP, AL/AL<sub>2</sub>O<sub>3</sub> MESH MICROPLASMA DEVICES: FORMATION OF MICRO-TIP ARRAYS AND DISCHARGE CHARACTERISTICS

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Monolithic arrays of Al/Al<sub>2</sub>O<sub>3</sub> microplasma devices have been fabricated from a single piece of aluminum mesh by a sequence of wet chemical processes. The aluminum mesh has cavities with longitudinal and transverse dimensions of 660  $\mu\text{m}$  and 610  $\mu\text{m}$ , respectively. Through wet electrochemical processes, we have successfully divided the mesh into electrically isolated but parallel conduction paths in which micro-Al tips are formed at the mesh junction points. The minimum distance from one tip to another on an adjacent line may be varied from 80  $\mu\text{m}$  to 660  $\mu\text{m}$ . It is the distance  $d$  between successive tips that serves as the gap between two electrodes for a dielectric barrier device. The characteristics of microplasmas excited by this structure have been investigated in various noble gases under AC excitation. Strongly confined discharges producing luminance values  $>1500 \text{ cd/m}^2$  in 300 Torr of Ne have been observed between each of the adjacent micro-tips. The behavior of these microplasma arrays has been investigated over the 200-700 Torr range and their unique characteristics and optical properties will be described.

## DEGRADATION STUDY OF LEAD ZIRCONATE TITANATE FOR USE IN A FERROELECTRIC PLASMA SOURCE

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Ferroelectrics are a unique class of materials that exhibit a reversible spontaneous electric polarization. Lead Zirconate Titanate (PZT) is a solid solution of lead zirconate and lead titanate, in the structure of a perovskite. This particular ferroelectric has been implemented in a variety of applications, namely as plasma and particle sources. PZT has a high relative permittivity, as well as a high Curie temperature; thus, it is well suited to be used in this manner.

However, ferroelectric plasma sources, including ones based on PZT, will often degrade during use and fail completely. The objective of this research is to test hypothesized methods of degradation in an effort to better understand the destruction of ferroelectric plasma sources. By considering the plasma-material interactions that take place in this system, these sources can be optimized and tailored to specific implementations.

The primary sources of degradation considered here are (1) dielectric heating beyond the Curie temperature, (2) removal of oxygen from the perovskite structure, and (3) adjustment of the Zr/Ti ratio. While other methods of degradation are possible, only these three are considered in this work.

The experimental setup makes use of a variety of diagnostics, including; a residual gas analyzer (RGA), optical emission spectrometer, Faraday cup, and a double Sawyer-Tower circuit. The RGA measures any oxygen loss, as well as Zr or Ti that is removed from the sample. The spectrometer passively measures plasma parameters such as electron temperature and electron density via line ratios, as well as present species concentration via actinometry. The Faraday cup measures the emission currents and energies of electrons or ions as a means of determining efficiency; while the Sawyer-Tower circuit measures quantities unique to ferroelectrics, particularly the remnant polarization and coercive field.

After destruction, materials characterization is carried out with several techniques. Auger Electron Spectroscopy measured atomic fractions as a function of position and depth within the sample to determine Zr/Ti ratio and oxygen content and therefore damage. X-ray Diffraction determines the crystalline structure of the sample and thus its location on the PZT phase diagram. Scanning Electron Microscopy yields information about grain size and presents reveals any small-scale damage to the sample. In addition, profilometry quantitatively measures surface characteristics and macroscopic damage occurring from use.

The results are intended to present a clear insight into the degradation of PZT-based ferroelectric plasma sources.

## PLASMA DIAGNOSTICS OF UNDERWATER ELECTRICAL DIAPHRAGM DISCHARGES FOR TEXTILES TREATMENT

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A lot of intensive basic research has been performed in the field of textiles and technical textiles in the last years. The common problems such as wettability and adhesion, together with the environmental driven forces have increased nowadays the industry's interest in this field. This research delivers new materials with new possibilities, which open perspectives to resolve production problems or even develop completely new applications.

The discharge was generated in a narrow slit of 0.1 ~1 mm positioned between two metallic electrodes at 2 cm mutual distance. Both electrodes and the slit (diaphragm) were immersed in water medium. The electrodes were connected to a pulsed HV power supply based on the double rotating spark gap. The maximum peak voltage reached a value of 40 kV DC and the maximum repetitive rate of pulses was 60 Hz. We used different water based media in this study: CO<sub>2</sub> saturated mineral water, Cu<sup>2+</sup>, H<sub>2</sub>SO<sub>4</sub>, HNO<sub>3</sub>, H<sub>3</sub>PO<sub>4</sub>.

The discharge manifests itself as thin plasma filaments propagating along the textile surface (polypropylene and cellulose) up to the distance where the metallic electrodes are positioned. The filament propagation length is directly influenced by the conductivity of water solution, the amplitude of the applied voltage, and the speed of the fabric movement.

The plasma parameters such as electron number density  $n_e$ , temperature of electrons, and excitation temperature, have been measured by optical emission spectroscopy completed by the voltage and current measurement. The sampling optical fiber was installed directly in the slit to minimize the water absorption of light emission.

The determination of  $n_e$  from  $H_{\beta}$  in case of selected quantities at optimized parameters show that their values do not influence significantly electron density and its fluctuation is almost covered with the confidence interval. It was found that the effect of CO<sub>2</sub> bubbles as well as the role of Cu<sup>2+</sup> solution (or other metallic atoms) can bring interesting application.

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## RECENT PROGRESS IN APPLICATIONS OF COPLANAR SURFACE BARRIER DISCHARGES FOR LOW-COST HIGH-SPEED MATERIAL PROCESSING

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Diffuse Coplanar Surface Barrier Discharges (DCSBD) are capable of generating visually uniform high-power-density diffuse plasmas in any working gas, including pure atmospheric-pressure oxygen, without the use of He or Ar. DCSBD is a type of dielectric barrier discharge generating a thin plasma layer on the surface of a dielectric barrier with embedded electrodes, which appears to be advantageous to surface treatment and deposition processes. Very high plasma power densities achieved ( $\sim 100 \text{ W/cm}^3$ ) allows for short plasma exposure times on the order of 0.1 s and, consequently, high treatment speeds. An important construction advantage DCSBD-based devices is that they produce uniform plasma emission over a greater surface area than previous plasma generators and, consequently, they are well suited for treating surfaces of flat materials, including fabric, web, glass, paper and thin metal sheets.

A DCSBD-based plasma treatment system will be described that permits permanent hydrophilization of light-weight polypropylene nonwovens (PPNW) on a continuous web handling system similar to a corona treating system with low power consumption of approximately 1 kWh/kg. In addition the results on nitrogen plasma activation and post-plasma acrylic acid grafting, chitosan and nano-powders immobilizations onto PPNW will be presented. Another fabric-treatment application of DCSBD discussed is the surface treatment of PES cords resulting in significant improvement of the adhesion to rubber.

Besides the fabrics treatment applications, the paper will review a current state of the art and opportunities for the use of DCSBD plasma surface treatment in the coating and conversion of paper products, glass and aluminium surface cleaning, and wood surface treatment.

## **LOCALIZED SURFACE TREATMENT USING A MICROWAVE GENERATED SURFACE WAVE MICROPLASMA**

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The objective of this project is to do materials processing on spatially localized areas by applying a small discharge to only the region being processed. A small diameter stream of plasma (less than 2 mm in diameter) is created by using microwave energy to create a discharge inside a tube. The discharge then flows out the end of the tube onto the surface being processed delivering ions and reactive radicals. The diameter of the plasma stream from the tube to the material being processed is controlled by an aperture mounted at the end of the tube. The spot size of the localized plasma stream ranges from 2 mm down to 10's micrometers depending on the aperture size. The discharge is created by using 2.45 GHz microwave energy that is coupled into the discharge using a small re-entrant cavity that has a hollow inner conductor and a small capacitive gap at the end of the cavity. A processing gas mixture is fed through a 2 mm inner diameter (i.d.) quartz tube which is located inside the hollow inner conductor of the cavity. This tube is exposed to a high electric field at the small gap of the cavity thus generating the surface wave plasma. The length of the surface wave discharge in the tube can be extended by increasing the microwave power to the discharge so that the plasma reaches the aperture. At the end of the tube the plasma stream does materials processing to a substrate that sits on a CAD-guided XYZ stage. A radio frequency (RF) bias is applied between the aperture and the substrate holder to increase the ion energy. The operating pressures range from 0.5 Torr to 10 Torr. The microwave powers utilized ranges from a few Watts to 10's Watts. Experimental results for etching localized regions on the surface of an ultrananocrystalline diamond (UNCD) thin film with an argon/oxygen discharge will be presented. The surface profile produced on the UNCD after the etching process will also be quantified.

This paper also reports on measurements of the plasma density of argon discharges operated in the microplasma structure using double Langmuir probe placed in the processing area. Additionally, initial simulations of the plasma excitation using the reentrant cavity will be presented.

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## REDUCTION OF GASEOUS DIMETHYL SULFIDE (DMS) USING COAXIAL DIELECTRIC-BARRIER DISCHARGE AT ATMOSPHERIC PRESSURE

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Dimethyl sulfoxide (DMSO) is a required chemical that is extensively used in the manufacturing process of e.g., TFT-LCD. DMSO is used in the process as a stripper and stripping cleaner for photo-resist removal. After stripper process and biodegradable treatment of DMSO wastewater, Dimethyl Sulfide (DMS) as a by-product is the most abundant species induced from DMSO; it produces unpleasant smell and seriously impacts the clean-room procedures. An effective treatment for DMS is a thus critical issue for the related industries. In the study, coaxial dielectric-barrier discharge (DBD) configuration with a glass capillary tube is employed to destroy the DMS using argon micro-plasma. Optical Emission Spectroscopy (OES) with oscilloscope is utilized for detecting real-time excited species and measuring energy transmission efficiency. The residual compounds after the treatment are detected by Gas Chromatography based technology combined with Flame Photometric Detector and Thermal Conductivity Detector (GC-TCD). FTIR combined with 9.6 meter gas cell is applied. A probable dissociating mechanism of gaseous DMS is thereafter suggested. The result demonstrated the maximum capacity of DMS added into ignitable argon plasma was 500 ppm. Both C<sub>2</sub> and H<sub>2</sub> peaks were observed by OES at 250 and 500 ppm, while CS peak was found with a concentration of 500 ppm. Hydrogen was also observed by GC-TCD. Based on lower bonding energy of C-H (3.5 eV) with respect to that of C-S (5-7eV), the C-H was easily dissociated into C<sub>2</sub> and H<sub>2</sub>. Since the overall acquired energy is a constant, as the content of DMS increases, the supplied energy is insufficient to dissociate DMS thoroughly, which results in the presence of CS peak in the spectrum. In addition, OCS and CO compounds were subsequently present in FTIR spectra, as a high concentration of DMS remained in an air sample bag and contacted with air.



## THE FUNDAMENTALS OF MICROPLASMA SOURCE FOR THE ANALYSIS OF GASES BY THE METHOD OF COLLISION ELECTRON SPECTROSCOPY (CES)

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In [1-3] a new method of gaseous media analysis and the ionization detectors for its realization has been patented. It is based on new concept of Collisional Electron Spectroscopy (CES). The method CES allows to analyze energy of electrons generated during ionization of atomic or molecular impurities at a high pressure (for details, see [1-3]). Dimensions of ionization cell are chosen so that the electrons energy distribution is formed in non-local regime. In such a way the electrons reach analyzing electrode, losing only a portion of their initial energy which does not exceed a predetermined level. In present report the results of a full-scale modeling of a pulsed micro-plasma source for CES are presented. Radius of electrodes is  $R=0.5$  mm, interelectrode gap is  $L = 0.1$  mm, the volume is filled with buffer helium at the atmospheric pressure. The self-consistent system of equations for concentration of charged and excited particles was solved in 2D geometry. The rates of plasma-chemical reactions with participation of electrons and their transport coefficients were determined by solving the kinetic Boltzmann equation. The self-consistent electric field was calculated using Poisson equation. Spatial-temporal profiles of charged and excited particles (atomic and molecular) are presented as for the active, so for post-discharge phases. The results demonstrate that the microplasma source makes it possible to obtain relatively high densities of metastable and charged particles necessary for CES implementation. References. [1]. A.A.Kudryavtsev and A.B.Tsyganov. Gas analysis method and ionization detector for carrying out said method. RU Patent <sup>1</sup> 2217739, issued November 27, 2003. [2]. A.A.Kudryavtsev and A.B.Tsyganov. Gas analysis method and ionization detector for carrying out said method. Int. Patent PCT WO2004/036206, issued 2004-04-29. [3]. A.A.Kudryavtsev and A.B.Tsyganov. Gas analysis method and ionization detector for carrying out said method. US Patent 7309992, issued December 18, 2007.

## TIME RESOLVED SPECTROSCOPIC MEASUREMENT OF HIGH-POWER PULSED MICROPLASMA FOR ELEMENTAL ANALYSIS

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Atmospheric ICP (Inductively Coupled Plasma) has been widely used for elemental analysis because of its excellent excitation/ionization ability. Recently, one of the most important targets of elemental analysis has shifted to smaller amount samples such as nano-particles, bio-cells, etc. However, conventional ICP source has too large volume and so consumes large amount of samples (~1mL/min). To analyze small amount samples more efficiently, and to realize high performance mobile elemental analysis system, we have studied and developed high-power microplasma source.

With this device, stable plasma can be generated at a few watts of dc electric input power and with small amount of plasma gas (ca. 200 mL/min). However, input power to the microplasma was limited to a few watts because of electrode melting or damage. So the temperature and the electron number density are not high compare with the conventional Ar-ICP, and it causes insufficient analytical performance. To prevent the electrode from overheating and to achieve stable plasma generation, a very short (less than 1 us) but high voltage (up to 3 kV) pulse is applied for plasma ignition and then a long (about 10 us) and relatively low voltage (up to 0.5 kV) pulse is applied for plasma sustainment and excitation/ionization of analytes. As a result, up to 40 kW of the peak electric input power is achieved and aqueous sample introduction turned to be available. With typical ultrasonic nebulizer, 100 ppm yttrium aqueous sample was introduced and 100 ppb of detection limit was achieved based on the observed emission line of Y (II) 371.03 nm.

To reveal the excitation/ionization sequences in the microplasma, time resolved spectroscopic measurements were carried out. The sequential drift of the plasma properties such as the temperatures and the excitation/ionization extent will be discussed.

## DEPOSITION OF DIAMOND-LIKE-CARBON FILMS USING TRANSIENT GLOW MICRODISCHARGES POWERED BY FAST PULSE-TRAIN VOLTAGES AT ATMOSPHERIC PRESSURE

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We discussed transient glow microplasmas powered by fast pulse-train voltages and their applications to the deposition of diamond-like-carbon (DLC) films at atmospheric pressure. The DLC features high mechanical hardness, low friction coefficient, and high electrical resistivity, and is widely used as coating material of magnetic disks, metallic dies, and plastic bottles. The conventional method to deposit the DLC films is based on vacuum processes. However, growing applications of the DLC films in industry demand fast and inexpensive deposition processes. An atmospheric pressure deposition system is one of the promising candidates for the solution.

Atmospheric pressure glow discharges (APGDs) tend to shrink into a thin current channel forming arc discharges, which is well-known as a glow-to-arc transition (GAT). Recently, utilization of microplasmas was proposed as a novel method to generate stable APGDs. The small size of the microplasma obstructs the growth of spatial instabilities and enhances the cooling of the excess heat contributing to the GAT. Although the utilization of the microplasmas is the effective approach to generate the stable APGDs, the high-power injection to the discharge causes the evolution of crucial instabilities.

In the previous study, a high-pressure glow microplasma was obtained by the transient glow discharge in which pulsed voltages were made zero before the GAT. It is also possible to obtain high-power density glow microplasmas. However, the significantly short duration of the transient glow microplasma resulted in a low time averaged injection power and an insufficient deposition rate.

In this study, we developed a method to generate the transient glow microplasmas using high-voltage pulse-trains which consisted of several pulses with short duration. The pulse-train generator was composed of fast semiconductor switches and a nonlinear transmission line (NLTL) in which chip monolithic ceramic capacitors were used as a nonlinear element. The pulse duration and the interval between the individual pulses were 40 ns and 80 ns respectively. The equivalent repetition frequency was 12.5 MHz. With fast miniature gas flows of the mixture of methane and helium, the transient glow microplasma was obtained. A stabilization effect for the discharge due to highly repetitive operation made it possible to deposit the DLC film on a stainless steel plate cathode with the deposition rate of up to 1.5  $\mu\text{m}/\text{min}$ . The characterization of the DLC film was carried out using SEM observation, Raman spectroscopic analysis, and hardness measurement with a nanoindenter.

## CHARACTERIZATION OF ARC EXTINCTION USING PULSED MICRO-ARC DISCHARGE WITH CO<sub>2</sub> GAS BLASTING

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Gas circuit-breaker is a switch gear to protect electric power system from overvoltage, overload, and line faults appearing in the power transmission lines. A direct observation of arc extinction behavior in the gas circuit-breaker is difficult because the contacting electrodes are located in the big metal housing of the gas circuit-breaker. Experiments for obtaining data on the arc extinction processes also cost a lot of money. We tried to use a pulsed micro-arc using a miniature gas flow system, which is easy to control the various discharge parameters, namely, flow velocity, kind of gas and gap distance, for characterizing the extinction of arc. In this paper, we discuss the blasting effect on the arc by dry air or CO<sub>2</sub> gas flowing in the parallel direction to the electrodes. The arc voltage increased with increasing the gas flow velocity because the arc column was squeezed by the effect of the gas flow and then the current density increased. It was confirmed that the arc diameter decreased at the center of the gap in the images taken with a high-speed camera. The arc temperature at 5 $\mu$ s before the current zero was examined by measuring the emission intensity ratio of copper atomic lines. The integrated emission intensities were correlated to the temperature by Boltzmann formula. The arc temperature was in the range of 9000-10500K. At the same time, the power loss was obtained using the Mayr's equation. The power loss increased with increasing the gas velocity. The current interruption probability for the CO<sub>2</sub> gas flow was higher than that for the air flow. A great amount of electronegative species such as O<sup>-</sup> was generated in the dissociation reaction of the CO<sub>2</sub> gas. If the gas velocity increased, the current interruption probability was improved.

## NEW SUSTAIN WAVEFORM FOR IMPROVING THE LUMINOUS EFFICACY IN A WIDE GAP PLASMA DISPLAY

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One pixel of AC plasma display panel (PDP) has three electrodes within its tiny discharge volume less than a few tens of Pico liters. One is address electrode and the others are surface electrodes positioning at the opposite plate of the address electrode. The surface electrodes make main discharges to illuminate the pixel. The gap between the surface electrodes is about 50~80  $\mu\text{m}$  which is determined to establish the lower firing voltage between the surface electrodes under various environmental conditions. The  $P \cdot d$  (pressure  $\times$  distance) value in a current PDP is located on the right side of the Paschen minimum, thereby widening the gap between the surface electrodes seems to be unattractive. In spite of the demerit increasing firing voltage, however, widening the gap has a few merits such as low capacitance and high luminous efficacy. It can reduce simultaneously the discharge and reactive powers. However, recent study on a wide gap structure has reported the luminous efficacy has a strong dependence on driving frequencies.[1] The volume of discharge in a high frequency driving is shrunk compared to those in low frequencies, thereby the luminance is seriously decreased while the discharge current remains almost constant.

In this paper, we investigate the mechanism of low efficacy in a high frequency driving and suggest a new driving waveform for improving the efficacy. The detailed role of the address electrode during the surface discharge is discussed.

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## NON-THERMAL PLASMA DEVICES AT ATMOSPHERIC PRESSURE FOR BIOMEDICAL APPLICATIONS

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Atmospheric pressure plasmas (APPs) have been recognized as a new paradigm in the biomedical applications. APPs proved its effectiveness to be used in the field of biomedical for the treatment of living cells, sterilization, blood coagulation, wound healing, and air purification [1]. Many devices for APPs were operated by DC, AC, pulse, RF, and microwave sources [2]. Air, argon (Ar) and helium (He) plasma devices were presented for the treatment of cancer cells, sterilization, tooth whitening, and blood coagulation in this study.

Non-thermal air plasma was generated by two electrodes covered with a dielectric material. One electrode was connected to sinusoidal (20 kHz) high voltage (5 kV) source and the other electrode was grounded. The target was G361 human melanoma skin cancer cell. Antibody conjugated 30 nm gold nanoparticles which enhance the therapeutic effects of the plasma were used. After 40 sec treatment, the death rate of cancer cells increased about 74% compared to only plasma treatment without any conjugation [3].

The atmospheric pressure plasma jet (APPJ) for the sterilization consists of Al electrode with 1mm hole and dielectric tube. A sinusoidal (20 kHz) high voltage source (~kV) was applied to the Al electrode and Ar and He gas with a flow rate of 4 slm were used as working gases. It tooks non-thermal APPJ several tens of second to kill the 90% bacteria.

The new non-thermal APPJ was developed for enhancement and acceleration of tooth whitening effect with H<sub>2</sub>O<sub>2</sub>. The APPJ used for He gas driven by AC was made of a tube structure dielectric material and two (inner and outer) electrodes. After the plasma treatment with H<sub>2</sub>O<sub>2</sub>, a 220% improvement of the tooth whitening was observed. The enhancement was attributed to considerable OH radical generation.

The micro-plasma source based on a coaxial transmission line resonator (CTLR) has been designed and applied to the blood coagulation. The CTLR plasma source consists of a coaxial transmission line where one end point is short and the other end point is open. After 15~20 seconds of treatment for mouse blood, the blood was changed into the clot in part and coagulated.

In conclusion, non-thermal APPs operated by AC and micro-plasma operated by microwave can be applied to various biomedical applications such as treatment of cancer cells, sterilization, tooth whitening, and blood coagulation.

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## THE EFFECT OF ATMOSPHERIC PRESSURE MICRO PLASMA ON THE DEGRADATION OF INTEGRINS AND FOCAL ADHESION KINASE IN G361 MELANOMA CELLS

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An RF-driven nonthermal atmospheric micro-plasma has been applied for the treatment of melanoma cells. Increased expressions of integrins and focal adhesion kinase (FAK) is important for the survival, growth, and metastasis of melanoma cells, and hence degradation of integrin and FAK proteins may be a good method for melanoma therapy. We investigated the effects of a low-temperature micro-plasma on adhesion molecules of G361 melanoma cells. Micro-plasma irradiation induces (1) significant cell detachment from the bottom of microtiter plates coated with collagen (2) cell death, inhibits (3) the expressions of integrin  $\alpha_2$ , integrin  $\alpha_4$ , and FAK on the cell surface, and (4) results in well-stretched actin filaments changing to a diffusive pattern. These results suggest that an atmospheric micro-plasma strongly inhibit the adhesion of melanoma cells by reducing the activities of integrins and FAK.

## INFLUENCE OF PLASMA CHEMISTRY ON THE PLASMA NEEDLE-BIOMATERIAL INTERACTION

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The atmospheric pressure RF-excited plasma needle is a non-thermal discharge sustained at the sharp tip of a needle in helium gas flow. The plasma needle has been applied to various biomedical applications. However, the mechanisms of the plasma-biomaterial interaction are only poorly understood. In this study, we focus on influences of humid air diffusing into the discharge domain on plasma chemistry. Our fluid model includes 46 species and over 200 elementary reactions in one-dimensional spherical coordinates. An expected concentration gradient of humid air is assumed to be present due to back diffusion of air against helium convective flow. Our simulation results indicate that charged particle density distribution near the treated surface is relatively insensitive to the humid air concentration. The distributions of neutral density, including metastables and radicals, strongly depend on the humid air concentration. When the humid air concentration is low ( $\sim 10$  ppm) near the treated surface, the dominant species are atomic/molecular helium metastables. On the other hand, when the humid air concentration is high ( $\sim 0.1\%$ ), various species such as O,  $O_2^*$ , N,  $N^*$ , OH and H are created mainly by electron impact excitation and dissociation. Most interestingly, ground state atomic oxygen shows the highest flux onto the treated surface of all. Considering experimental observation of the ring-shaped bacteria killing pattern, our simulation results suggest that ground state atomic oxygen plays a central role in the activation of bacteria under conditions considered here.



## MICROPLASMAS AT THE TIP OF AL/AL<sub>2</sub>O<sub>3</sub> MICROSCOPIC ELECTRODES IN WATER OR SALINE SOLUTIONS

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Non-thermal atmospheric pressure plasmas in liquids is an active and growing research field. The pulsed corona discharge (~1 J/pulse) is the most widely used technique to ignite discharge in liquid media. [1] One drawback of the high power discharge is, however, the difficulty in controlling the discharge volume. On the other hand, a microplasma sustained at or near a microscopic electrode tip has a significant advantage with respect to controllability of the discharge. This mild discharge is also suitable for fragile materials such as cells/tissues. [2-3]

Microplasmas in liquid encompass various phenomena such as bubbles/vapor, shock waves, water jets, and liquid chemistry. Due to the complex nature of the liquid microplasma, the detailed mechanisms responsible for breakdown and surface interactions are not fully understood. In this study, we have fabricated Al micro-tip electrodes encapsulated by Al<sub>2</sub>O<sub>3</sub> which have been grown electrochemically. The diameter of tip is in the range of 20-30 micrometer and an additional thin protective layer of silicon nitride is coated onto the tip to increase its durability.

We will report voltage/current waveforms and emission profiles for microplasma generation in water and saline solutions. The influence of the dielectric on the electrode surface will be discussed by comparing the performance of the dielectric coated tip with that of a bare metal electrode. [4]

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## MICROPLASMAS PRODUCTION OF SINGLET OXYGEN AT ATMOSPHERIC PRESSURE FOR DNA OXYDATION

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Recently, we demonstrated <sup>[1,2]</sup> that the so-called *Micro-Cathode Sustained Discharge* (MCSD), a discharge concept first introduced by Schoenbach *et al* <sup>[3]</sup>, can be very effective for producing large amounts of singlet oxygen  $O_2(a^1D_g)$ . The generation of  $O_2(a^1D_g)$  by electrical discharges has recently attracted much attention because of its potential application for the pumping of the oxygen-iodine laser. However,  $O_2(a^1D_g)$  is also well known to produce cytotoxic effects, in such a way that the generation of high fluxes of  $O_2(a^1D_g)$  could have many biological applications. To be useful for biological applications, the  $O_2(a^1D_g)$  states must be created and transported over some 10's cm at atmospheric pressure, while laser application only requires pressures of about 100 mbar.

In the present work, we report on the possibility of using arrays of MCSD's operating in parallel to generate high fluxes of  $O_2(a^1D_g)$  at atmospheric pressure. Actually, we show that  $O_2(a^1D_g)$  number densities higher than  $10^{16} \text{ cm}^{-3}$  can be produced by arrays of MCSD's operating at atmospheric pressure in He/O<sub>2</sub>/NO mixtures at total flow rates up to 30 l/min, and transported over distances above 50 cm, resulting in  $O_2(a^1D_g)$  fluxes above 10 mmol/h. The effect of different parameters such as gas flows and mixtures, discharge current and voltage, and array geometry are discussed in the study. Preliminary experiments were conducted showing that 2'-deoxyguanosine (dGuo), the only DNA constituent known to react with  $O_2(a^1D_g)$  <sup>[4]</sup>, is decomposed when an aqueous solution of dGuo is bubbled with the downstream gas containing  $O_2(a^1D_g)$ . Work is in progress to determine the nature and amount of the generated dGuo decomposition products and to study in more details the reactivity of  $O_2(a^1D_g)$  with DNA in aqueous solutions.

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## INACTIVATION OF BACTERIA IN AQUEOUS ENVIRONMENT BY ATMOSPHERIC PRESSURE NON-THERMAL PLASMA

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Over 100 different types of bacteria, protozoa and viruses exist in contaminated water, which are responsible for several kinds of serious illnesses, kidney failure and degenerative heart disease. These contaminations are usually treated by chemical methods. Recently, different attempts have been made to inactivate bacteria in water with non-thermal plasmas (e.g., pulsed streamer discharge plasma, gliding arc discharge plasma). This research intends to study the inactivation of bacteria in aqueous environment by an atmospheric pressure non-thermal plasma micro jet (PMJ) generated with a device based on microhollow cathode discharge principle. *Staphylococcus aureus* was diluted and inoculated in sterile water to desired concentration. The PMJ was either suspended at 1 cm above the water surface or sustained in a quasi-steady gas cavity inside water. Temperature and pH of the water were monitored during the whole treatment process. The inactivation of bacteria is attributed the change of pH, direct attack of the cells by plasma generated species (photons, radicals, ions, excited atoms). Possible pathway will be briefly discussed.

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